Thermal Pollution: Its Production, Effects, and Control

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Thermal Pollution: Its Production, Effects, and Control

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I. INTRODUCTION

Thermal pollution is the common term used to describe the environmental effects of the discharge of heated cooling water from industries and steam-electric powerplants. Thermal pollution has been defined as ". . . an increase in water temperature which will or is likely to render the waters harmful to public health, safety, or welfare, or to a legitimate water use, or to cause a nuisance as a result of increased biological activity" (101, p. 984).

Since about 70% of the thermal pollution load in the United States is caused by the steam-electric power industry (22), the best single index of potential increase in thermal pollution is the proposed increase in electric power production. For the past 50 years electric power loads in the United States have grown at a rate requiring an approximate doubling of electric power capacity every 10 years (37). Forecasted load growth to the year 2000 indicates that expansion can be expected to continue in the same pattern or possibly even accelerate to a rate requiring a doubling of electric generating capacity every five years (98).

Currently, about 80% of the total electricity generated in the nation is from steam powerplants; and the majority of the remaining amount is generated by hydroelectric plants (56). As future power loads increase, power production will depend more and more on steam powerplants since there are few hydroelectric sites remaining that are capable of economic development; and other methods of power production, such as magnetohydrodynamics, have not yet proven commercially feasible. In addition to the expected relative increase in power production from steam powerplants, individual powerplants are being built larger to

achieve economies of scale. Cost savings of 30% to 40% can be realized in the production of power from a generating plant producing 1000 megawatts of electrical power (MWe) compared to one of only 100 MWe (98). The economies of scale are most pronounced in the large nuclear powerplants. This economy, plus the absence of major air polluting effluents, has added impetus to an accelerating trend to use large nuclear plants to generate electric power. Toyland (98) reports that the new nuclear plants planned for operation by 1973 average 624 MWe, whereas the average size of all units retired between 1961 and 1963 was 22 MWe. Figure 1 illustrates the projected growth of total electric generating capacity and the projected growth of generating capacity by the various types of powerplants. As noted previously, steam powerplants now generate about 80% of the total electricity produced; and of this 80%, only about 5% is produced by nuclear fueled steam powerplants. From Fig. 1 one can see that it is estimated that by the year 2000, the proportion of total electric power produced by steam powerplants will have increased to 95%. Most significantly, the proportion of this steam-powerplant-produced electricity that is produced by nuclear plants will have grown from the current 5% to about 60%.

Although nuclear plants produce considerably less air pollution than fossil fuel plants, they reject a larger amount of heat to cooling water, per kilowatt-hour (kwhr) of electrical power produced. Current materials technology limits the maximum steam temperature in a water cooled nuclear powerplant to a value lower than that attainable in modern fossil fuel plants (76). As a result, the thermodynamic cycle efficiency of a nuclear plant utilizing a water cycle is generally less than that of a modern fossil fuel plant. In a modern coal-fired plant, about

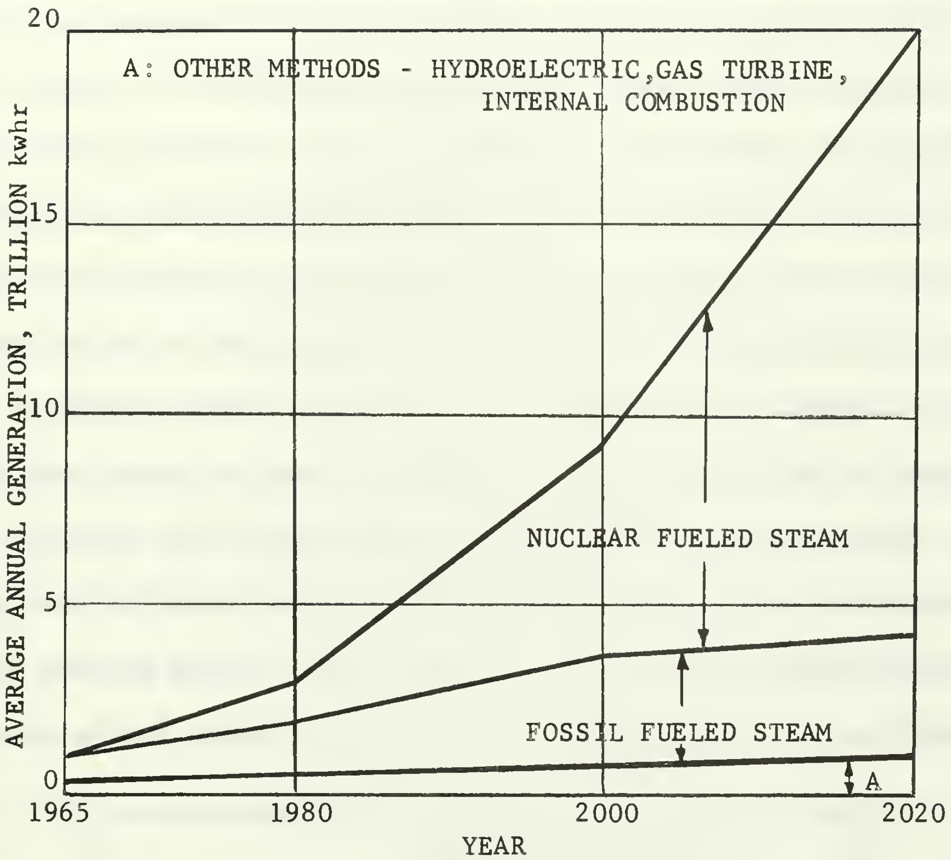


Figure 1. Projected electric generation by types of powerplants 1965-2020 (22).

4000 British thermal units (Btu) of waste heat are rejected to the cooling water for every kwhr of electrical power produced. In a nuclear plant, the amount of waste heat rejected to the cooling water increases to about 7000 Btu/kwhr because of the reduced plant efficiency (56).

A mitigating factor in the expanding thermal pollution problem is the fact that research on nuclear breeder reactors is progressing and they may be commercially available around 1980 (75). These reactor plants are expected to produce steam at temperatures approximating those now used in fossil fuel plants. The nuclear plant thermodynamic efficiency would then approach that of the fossil fuel plants and the amounts of waste heat rejected to cooling water by each type of plant,

per kwhr of electrical power produced, would be more nearly equal. A quantitative estimate of the total heat rejection rate from steam power-plants depends on the number of each type of plant (water nuclear, breeder nuclear, fossil fuel) in operation at the time. The projected heat rejection rate from steam powerplants is presented in Fig. 2 where it can be seen that by the year 2000, it is estimated that about 8.4 trillion Btu/hr of waste heat will be rejected by steam-electric power-plants to cooling water. The amount of cooling water required to dispose of this amount of heat is enormous. About 1 to 2 cfs of cooling water is needed for every megawatt of electrical power produced. A single 1000 MWe plant requires more than 500,000 gallons per minute (gpm) of cooling water - more water than is now used domestically each day in the entire state of Texas (49). The magnitude of the effects of

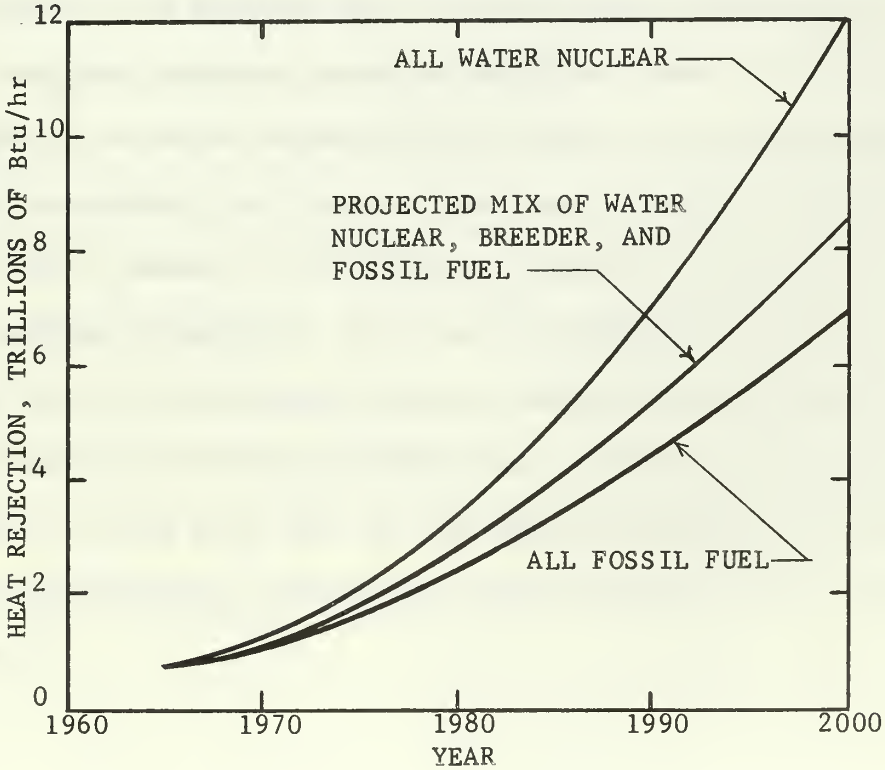


Figure 2. Projected heat rejection from steam-electric powerplants (56).

discharging 8.4 trillion Btu/hr to the nation's waterways is astonishing. This amount of waste heat is enough to continuously heat the total minimum fresh water runoff in the United States (220,000 cfs) by 168°F.

If current methods of plant cooling are continued to the year 2000, about 1,300,000 ft^3/sec of cooling water will be required to dispose of the rejected heat from all steam-electric powerplants (74). This amounts to about 50% of the total average fresh water runoff in the entire nation.

Mihursky (69) states that temperature is a very important, lethal, directive, and controlling factor in the aquatic habitat. It is lethal in that certain high or low levels can cause mortalities, directive in that it influences daily and seasonal behavior, and controlling in that it affects biochemical reaction rates and consequently influences metabolic rates. It is possible that the temperature changes caused in river, lake, and estuarine waters by powerplant waste heat discharge may become so extensive in the future, unless we reject more heat directly to the atmosphere, as to pose a considerable threat to fish and to aquatic life in general. This potential hazard to life and to the ecological balance of nature is the crux of the problem of thermal pollution.

The areas of the thermal pollution problem to be discussed in this paper include the production of waste heat in steam-electric powerplants, the effects of this waste heat on the aquatic environment, and methods and controls which will minimize the effects of waste heat on the aquatic environment.

II. PRODUCTION OF WASTE HEAT IN STEAM-ELECTRIC POWERPLANTS

2.1 Thermodynamics and Plant Thermal Efficiency

Thermal pollution is a natural consequence of the second law of thermodynamics which states that: "No actual or ideal heat engine operating in cycles can convert into work all the heat supplied to the working substance; it must discharge some heat into a naturally accessible sink" (36, p. 133). The basic purpose of the second law of thermodynamics is to define the extent of possible conversion of heat into work.

A cycle occurs, in the thermodynamics sense, when a mass of fluid in a particular thermodynamic state passes through a series of processes and returns to its initial thermodynamic state.

The thermal efficiency of a thermodynamic cycle is defined as:

$$\text{Thermal efficiency} = \frac{\text{Net work done}}{\text{Heat added}}$$

Because the first law of thermodynamics states that heat and work are mutually convertible, this expression can be rewritten as:

$$\text{Thermal efficiency} = \frac{\text{Heat added - Heat rejected}}{\text{Heat added}}$$

However, heat rate, which is the heat supplied per unit of power output, is the commonly used measure of powerplant efficiency. It is defined as:

$$\text{Heat rate} = \frac{3413}{\text{Thermal efficiency}} \quad \text{(Btu/kwhr)}$$

Heat rate is more descriptive of powerplant performance in that it expresses directly the amount of energy required by the plant to produce

a unit amount of power; and as indicated by the relation, a higher plant efficiency means a lower heat rate.

2.2 The Carnot Cycle

The most efficient thermodynamic power cycle is the Carnot cycle, which consists of two isothermal and two isentropic processes. The Carnot steam power cycle is depicted in Fig. 3 on a temperature-entropy (T - s) diagram. Wet steam at state point 1 is compressed isentropically to saturated liquid at state point 2. At this elevated pressure, heat is added at a constant temperature (T_2) as the water undergoes a

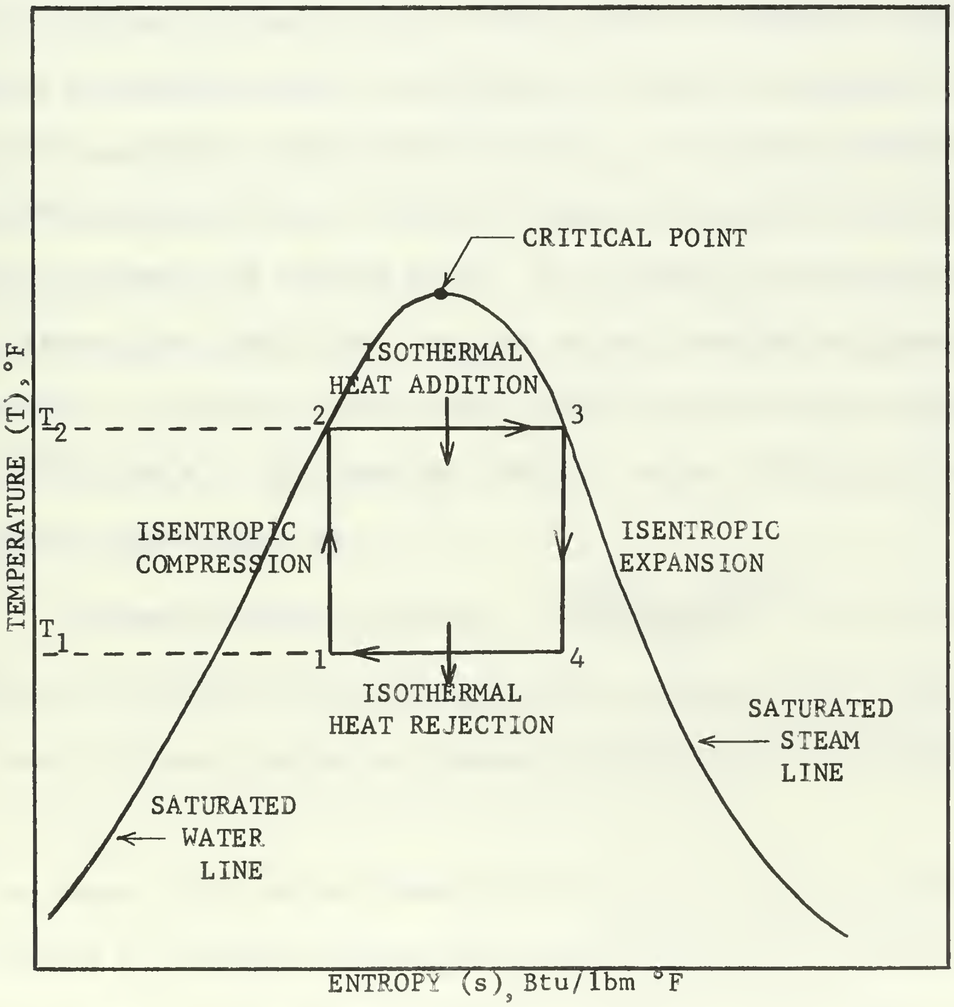


Figure 3. Carnot cycle using steam as a working substance.

phase change to saturated steam at point 3. The steam is then expanded through an ideal turbine to state point 4. Partial condensation at constant temperature (T_1) and pressure returns the steam-water mixture to state point 1. The thermal efficiency of this Carnot cycle is given as:

$$\text{Thermal efficiency (Carnot)} = \frac{T_2 - T_1}{T_2}$$

where: T_2 = absolute temperature of heat source in degrees Rankine (^oR)

T_1 = absolute temperature of heat sink (^oR)

The thermal efficiency of the Carnot cycle is important because it specifies the maximum limit of efficiency any cycle can achieve operating between the specified temperatures T_1 and T_2. In actual steam powerplant cycles the source of heat is the fuel (fossil or nuclear) and the sink is the environment via cooling water. As an example representative of modern steam plant conditions, the heat source temperature (gases of combustion) is typically about 2960^oR (2500^oF) and the sink temperature about 560^oR (100^oF). The limiting (Carnot) thermal efficiency obtained using these temperatures is:

$$\text{Thermal efficiency (Carnot)} = \frac{2960^oR - 560^oR}{2960^oR} = .81 \text{ or } 81\%$$

No current or proposed steam powerplant even approaches this value. The most advanced plants operate at thermal efficiencies of .45 (45%) or less.

The Carnot cycle is not practical to use in a steam powerplant. It is difficult to compress a two-phase mixture as required by process 1-2 in Fig. 3 (see p. 7); and the condensing process 4-1 would have to be controlled very accurately to end up with the desired quality at state

point 1. These impracticalities can be eliminated by modifying the Carnot cycle to the Rankine cycle.

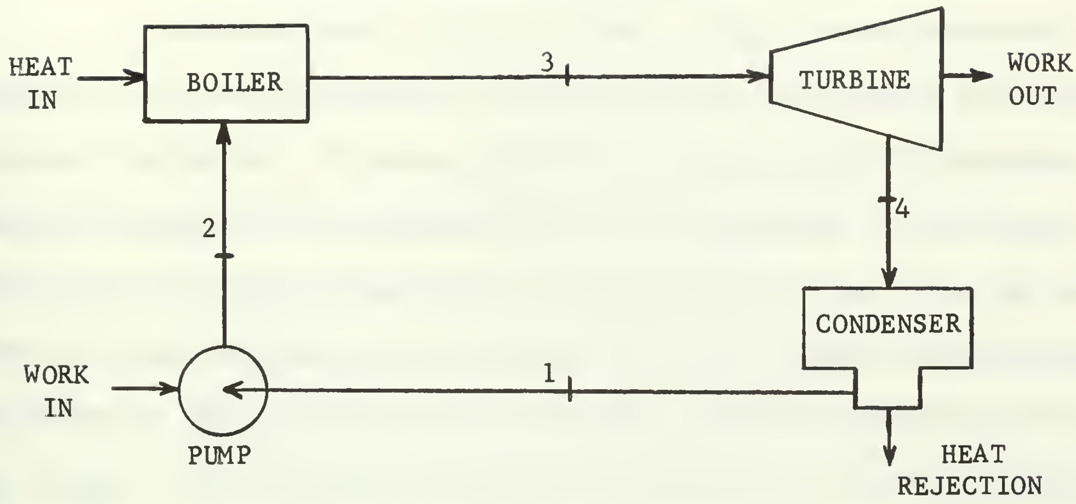
2.3 The Rankine Cycle

The Rankine cycle is the model cycle for steam powerplants. A simple powerplant operating on a Rankine cycle is illustrated in Fig. 4. Instead of condensing steam from the turbine exhaust (pt. 4) to a two-phase mixture, the condensation process is completed so that the wet steam leaving the turbine is condensed to saturated liquid (pt. 1). An ideal liquid pump then isentropically compresses the liquid to the pressure of the heat addition process (pt. 2). Heat addition occurs at a varying temperature, but constant pressure, as the subcooled liquid is raised to saturation temperature (process 2 - 2'). The amount of heat added at a varying temperature is small, however, compared to the latent heat of vaporization added in changing the saturated water to steam. Therefore, the Rankine cycle represents a close approach to the Carnot cycle. The ideal Rankine steam power cycle for a simple powerplant then consists of:

1. Isentropic compression in a pump.
2. Constant pressure, varying temperature heat addition in a boiler or steam generator.
3. Isentropic expansion in a turbine.
4. Constant pressure and temperature heat rejection in a condenser.

2.4 Methods of Increasing Rankine Cycle Efficiency

The efficiency of the Rankine cycle can be increased, on the basis of the theoretical Carnot cycle, either by decreasing the temperature at which heat is rejected or by increasing the average temperature at which heat is added.



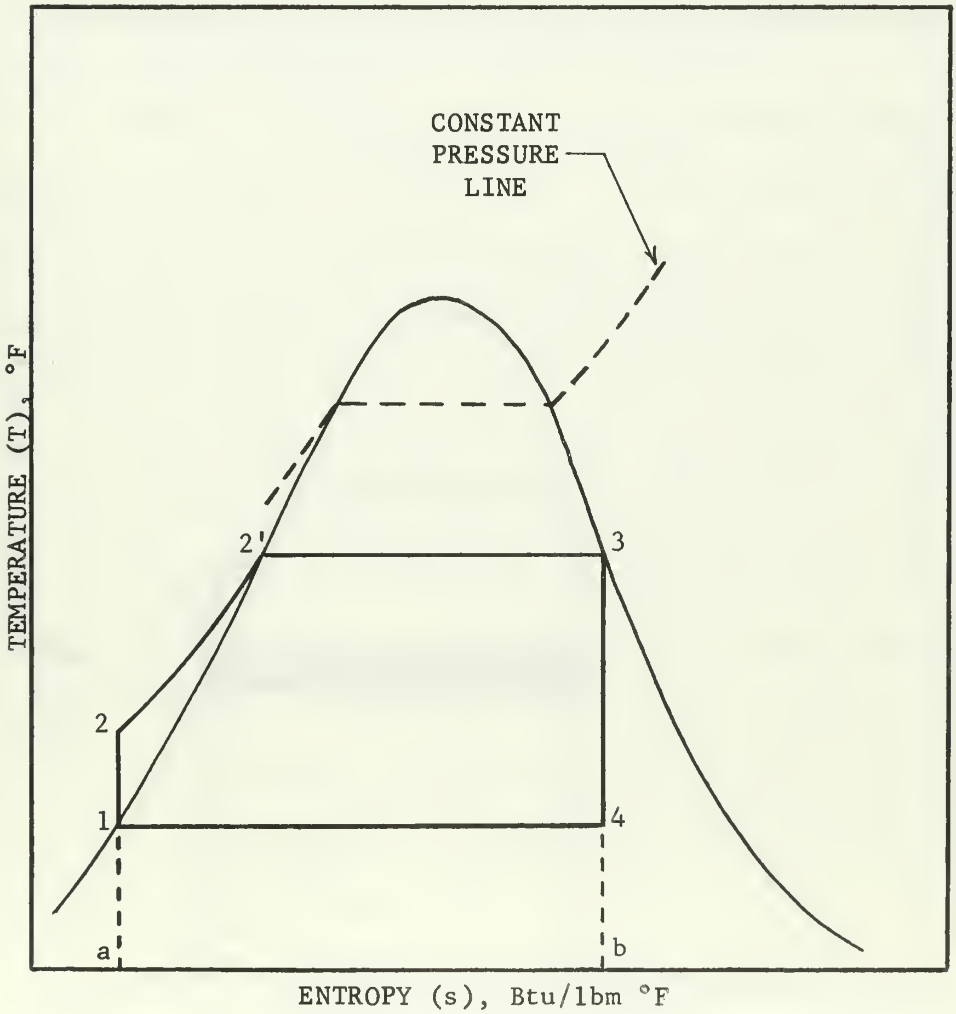


Figure 4. Simple steam powerplant operating on an ideal Rankine cycle.

2.4.1 Lowering Heat Rejection Temperature

Referring again to Fig. 4 (see p. 10), the area enclosed by points 2-2'-3-b-a-2 represents the heat added to the fluid in the steam generator or boiler. The area enclosed by points 1-4-b-a-1 represents the heat rejected to the cooling water in the condenser. The net work of the cycle is then represented by the difference in the areas for heat added and heat rejected, i.e., area 1-2-2'-3-4-1. Figure 5 illustrates the effect on the cycle of lowering the heat rejection temperature from T_{R1} to T_{R2}. The net work is increased by area 1-4-4'-1'-2"-2-1 shown by

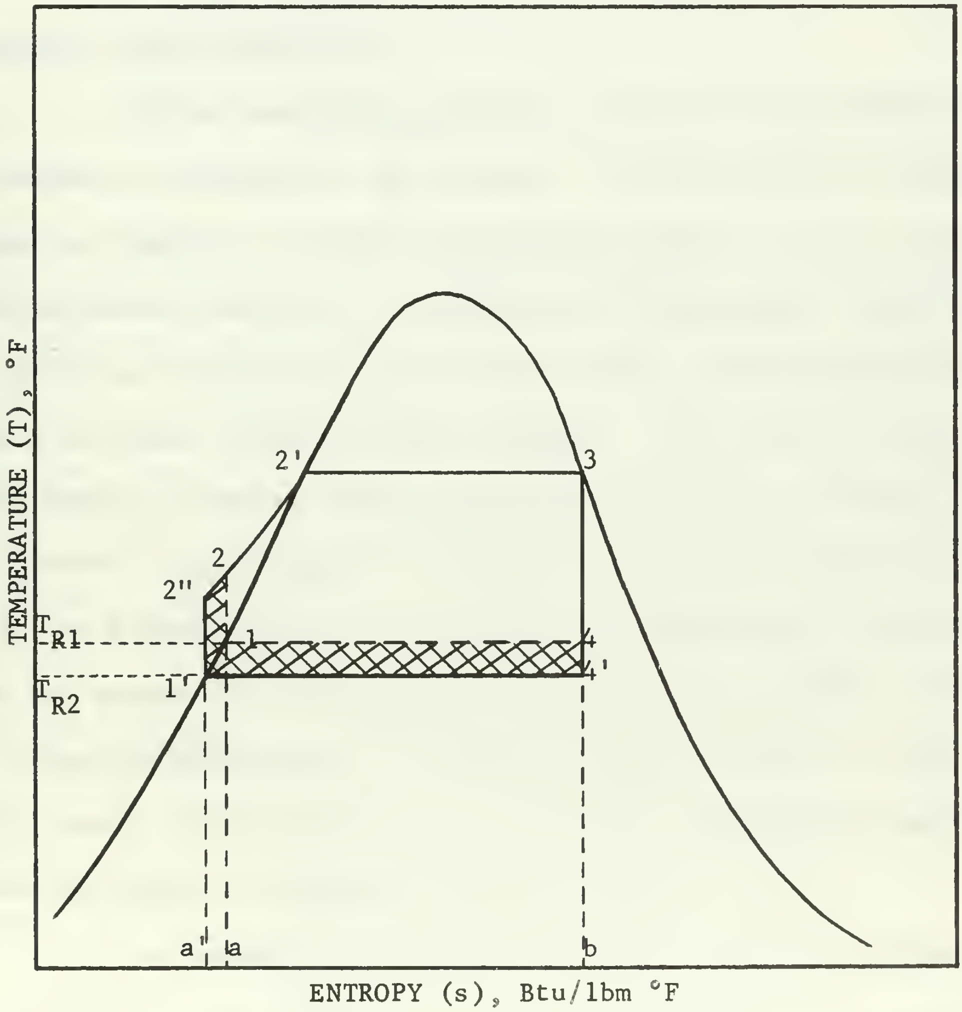


Figure 5. Effect of a change in heat rejection temperature on the ideal Rankine cycle (108).

cross hatching. The increase in required heat addition is indicated by area a'-2"-2-a-a'. These two areas are about equal, meaning that for each extra Btu of net work gained, only about one Btu of heat has to be added - a very efficient process. The net result of the addition of this highly efficient process to the overall cycle is a net gain in overall cycle efficiency.

A disadvantage of lowering the heat rejection temperature is that it causes an increase in the moisture content of the steam leaving the turbine. The increase in moisture content causes a decrease in turbine efficiency; and if the moisture exceeds 10%, serious erosion of the turbine blades may result.

Turbine condensers operate at saturated steam conditions with respect to temperature and pressure. Turbine exhaust (condenser) pressure is limited by condenser temperature which, in turn, is dependent on cooling water temperature. Lowering the cooling water temperature (heat rejection temperature) results in a lower turbine condenser temperature and lower turbine exhaust pressure. The relation between turbine exhaust pressure (heat rejection temperature) and plant heat rate (inversely proportional to thermal efficiency) is illustrated in Fig. 6. As a general rule, a 1 psi lower turbine exhaust pressure will reduce the amount of heat rejected to cooling water by about 2.5% (56). For a condenser operating at an exhaust pressure of about 1.5 psia (116°F), about a 35°F decrease in cooling water temperature would be required to reduce the exhaust pressure 1 psi.

The thermal efficiency of the power cycle is of prime economic interest in the operation of a steam powerplant and the interrelation of heat rejection temperature and cycle efficiency is an

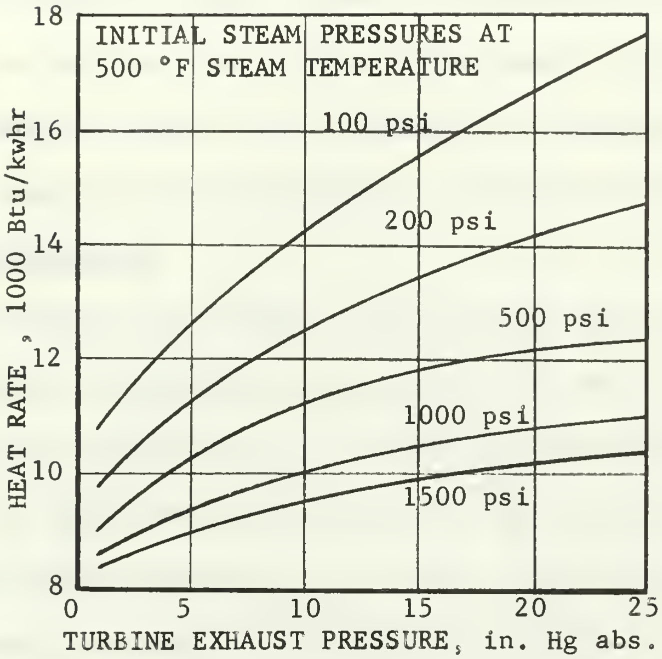


Figure 6. Effect of turbine exhaust pressure on powerplant heat rate (7).

important aspect of the thermal pollution problem. The lowest cooling water temperatures attainable by using artificial, closed, cooling-water systems, such as cooling towers or cooling ponds, are normally not as low as those occurring in natural waterways. If an electric power company is required to operate a powerplant with artificial cooling because of a thermal pollution hazard, not only will an extra capital investment be required for the cooling system but additional operating costs will be incurred throughout the life of the plant. The additional operating costs will result mainly from the additional fuel required because of the decreased plant thermal efficiency. Archbold (2) analyzes the cost of inefficiency for a 300 MWe plant, with a design heat rate of 9000 Btu/kwhr and a fuel cost of 30 cents per million Btu. For this plant, his analysis indicates that only a 1% increase in heat rate

(about a 1/2% decrease in plant thermal efficiency) will result in an added $70,956 in fuel costs per year. This example of the sensitivity of plant economics to plant thermal efficiency indicates the desirability of exploiting every practical technique to improve the plant efficiency.

2.4.2 Superheating

Increasing the average temperature at which heat is added will also increase Rankine cycle efficiency. One way to accomplish this is by superheating the steam above the saturated condition. Superheating results in a higher steam temperature at the turbine inlet without increasing the maximum pressure in the cycle. The maximum allowable steam temperature is normally established by metallurgical limitations of components such as superheater tubing and turbine blades. A T-s diagram for a Rankine cycle with superheat is shown in Fig. 7. The average temperature at which heat is added during the superheating process 3-3' is higher than the average temperature for the heat addition process 2-2'-3 which produces saturated steam. Therefore based on the Carnot cycle analysis, the efficiency of the cycle is increased. Another advantage of superheating is that the quality of the steam at the turbine exit (pt. 4') is improved over that resulting from a cycle without superheat (pt. 4).

Waste heat rejection is normally reduced by about 1.5% for every 50°F of superheating (56). For a typical modern fossil fuel plant, 350 degrees of superheat might be used which would therefore result in a 10.5% reduction in the amount of heat rejection and subsequent thermal pollution. The effect that superheating has on plant heat rate is shown in Fig. 8.

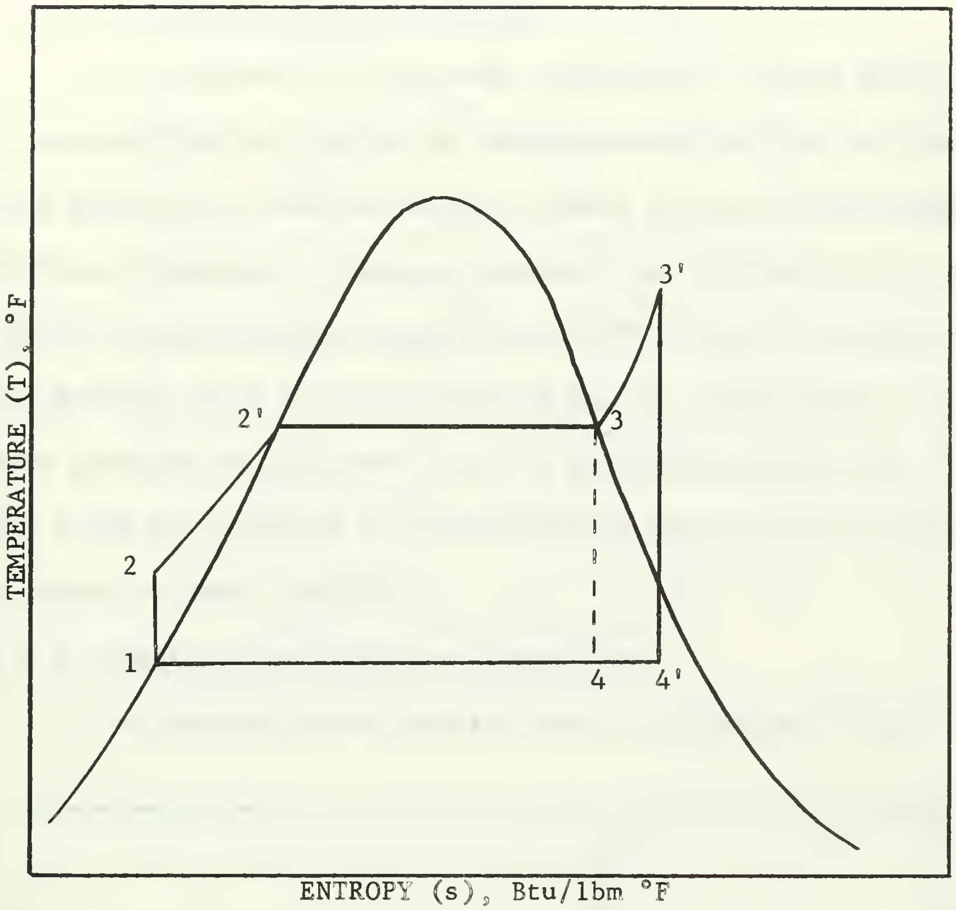


Figure 7. Effect of superheating on the ideal Rankine cycle.

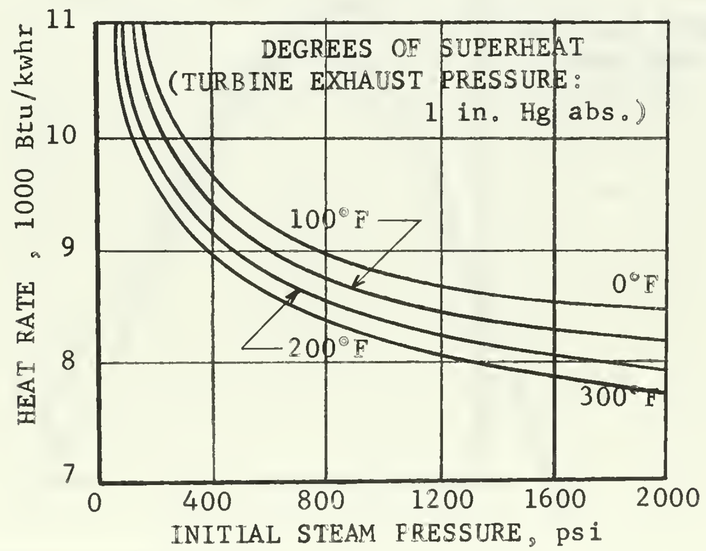


Figure 8. Effect of superheat on powerplant heat rate (3).

2.4.3 Increasing Maximum Pressure

An increase in the average temperature of heat addition may also be accomplished by raising the maximum steam pressure of the cycle. With this motivation, some fossil fuel plants are now being designed for supercritical pressures - pressures greater than the saturation pressure (3206 psia) at the critical temperature (705°F) (77). A simple supercritical Rankine cycle is illustrated in Fig. 9. The effect of increasing steam pressure on plant heat rate is presented in Fig. 10. In general, a 100 psi increase in steam pressure will reduce the amount of heat rejected by about .4% (56).

2.4.4 Reheating and Moisture Separation

One problem which results from a high pressure cycle, such

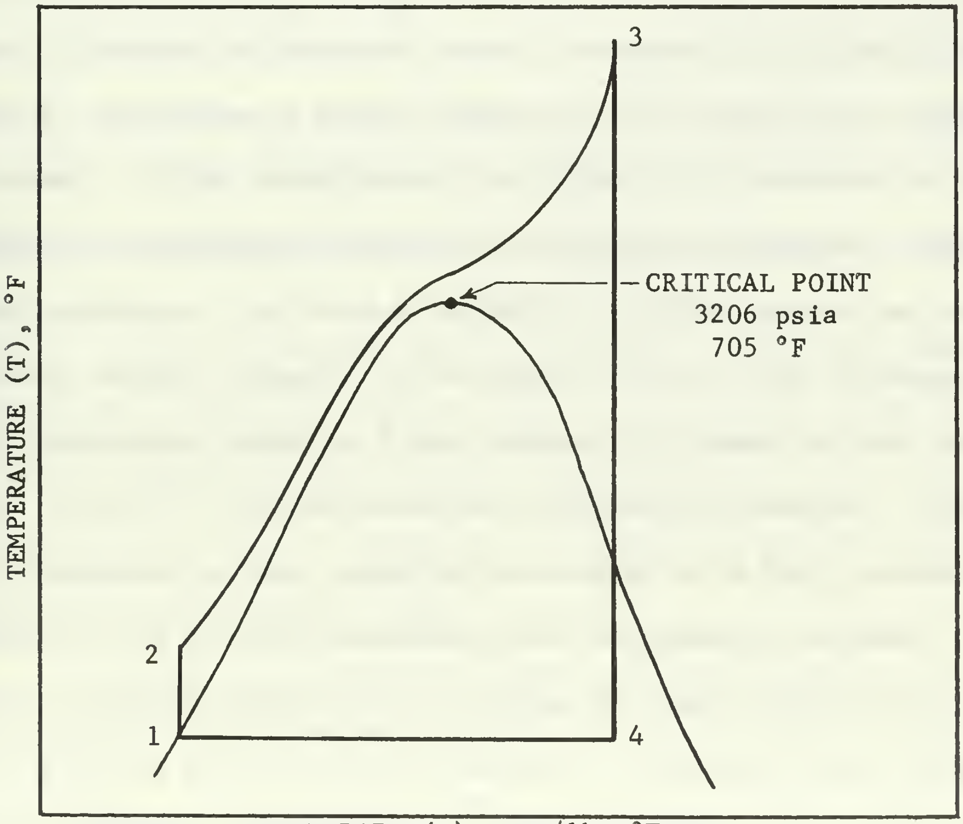


Figure 9. Ideal Rankine cycle with supercritical pressure.

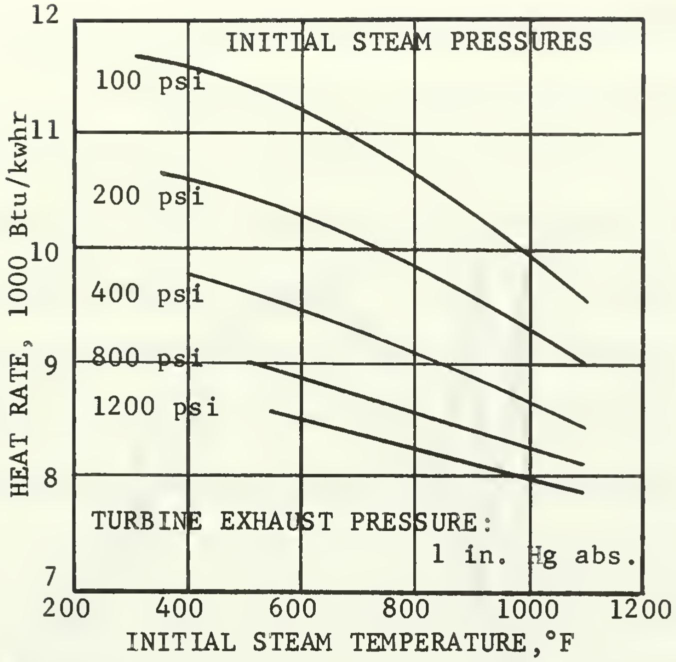


Figure 10. Effect of steam pressure on powerplant heat rate (3).

as a supercritical one, is high moisture content of the turbine exhaust steam. To reduce the moisture content, reheating is frequently used. Figure 11 illustrates a typical Rankine cycle utilizing both superheat and reheat. In the reheat cycle, the steam is not permitted to expand completely to condenser pressure in a continuous expansion. After partial expansion, the steam is extracted from the turbine and reheated at nearly constant pressure in the boiler, or in a heat exchanger using higher temperature steam as a heat source. The steam is then returned to the turbine for further expansion to condenser pressure. Typical steam powerplant turbine installations consist of a high pressure turbine and one or more intermediate and low pressure turbines. The steam is normally reheated after leaving the high pressure unit and before entering the low pressure turbines. It can be seen in Fig. 11 that the average temperature of the reheat process 3"-4 is about the same as that of the heat addition process 2-3' in the boiler or steam

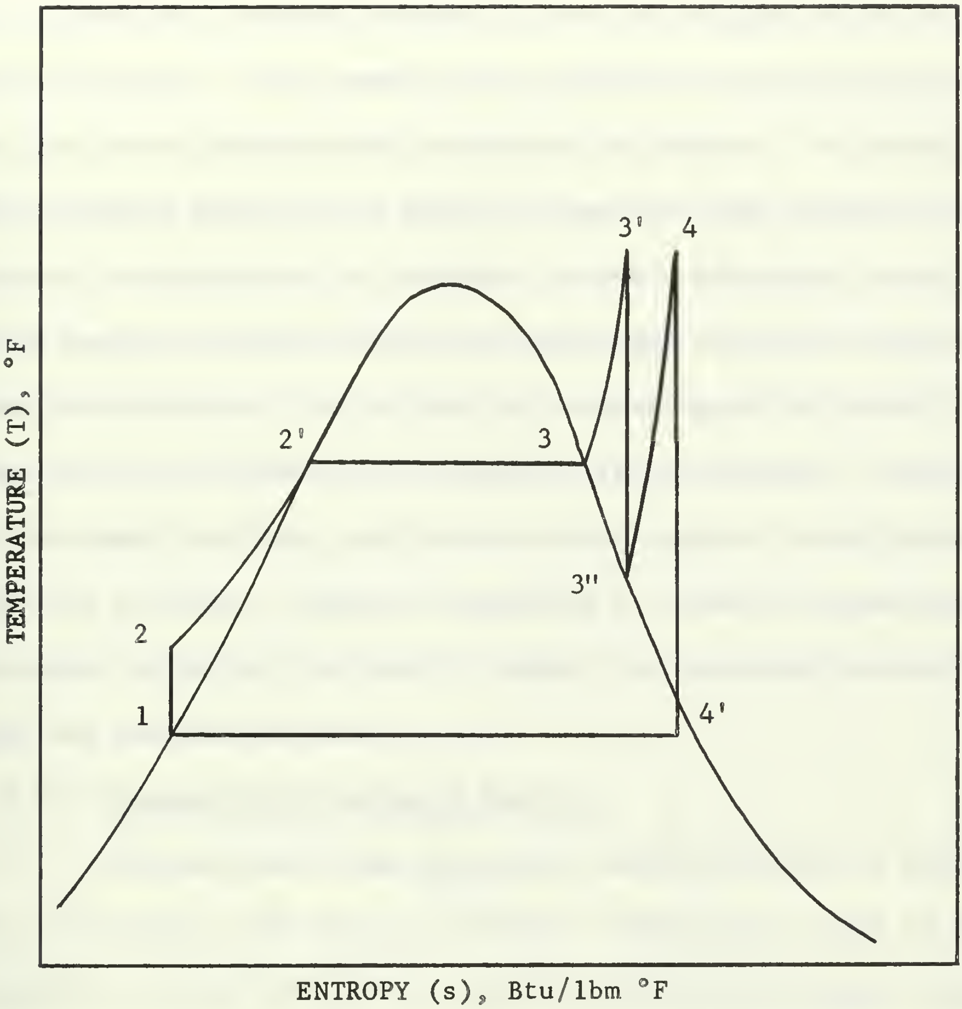


Figure 11. Ideal Rankine cycle utilizing superheat and reheat.

generator. However, a gain in thermal efficiency is realized from reheating due to the fact that the turbines using the dry reheated steam operate at a higher efficiency than if the steam had not been reheated. For each 50°F the steam is reheated, the amount of waste heat rejected will be decreased about 1.4% (56).

Few nuclear powerplants employ superheat because of materials limitations. Consequently, saturated steam is used in the turbines in these plants. If saturated steam at a representative pressure of 1000 psia is expanded through a turbine without reheat to a pressure of

1 in. Hg absolute, moisture content in the last stages of the turbine may reach 25% (31). The commonly used methods to reduce moisture content in nuclear plants are moisture separation and reheat. The steam is usually reheated after it has passed through the high pressure turbine and before it enters the low pressure turbine. Unexpanded steam is normally used as the heat source for reheating. Moisture separation may be done in addition to, or in place of, reheating and is normally accomplished at the same point in the steam cycle as reheating. However, moisture removal may also take place at each stage of steam expansion through the turbines. Moisture separation is normally accomplished by mechanically agitating the steam to remove the entrained moisture by gravity and centrifugal force.

2.4.5 Regenerative Feedwater Heating

No practical steam powerplant operates without a feedwater heater. For every 10°F rise in feedwater temperature, there is about a 1% reduction in heat that must be added in the boiler to make steam (3). Feedwater heating is accomplished by utilizing a heat source within the thermodynamic cycle other than the fuel i.e., regenerative heating. Referring to Fig. 11 (see p. 18) for a Rankine cycle with superheat and reheat, it is seen that for the sensible heat addition process 2-2', the average temperature is much below the average temperature of the vaporization, superheating, and reheating processes 2'-3 -3'-3"-4. The cycle efficiency is reduced because of this lower temperature heat addition process. Regenerative heating raises the average temperature of heat addition from external heat sources by preheating the feedwater using heat sources available internal to the cycle. This results in an increase in thermal efficiency. Depending on the number and arrangement

of feedwater heaters used, waste heat rejection to plant cooling water can be reduced by as much as 37% using regenerative feedwater heating (56). The ideal Rankine cycle with superheat, reheat, and regenerative heating is shown in Fig. 12. Part of the steam which enters the turbine at state 3' is extracted or bled from the turbine at point 3" after it has been partially expanded. The extracted steam is then directed to a feedwater heater where it is used to heat the subcooled feedwater from pt. 2 to pt. 2'. The extracted steam is normally returned to the cycle via piping to the turbine condenser after it has heated the feedwater.

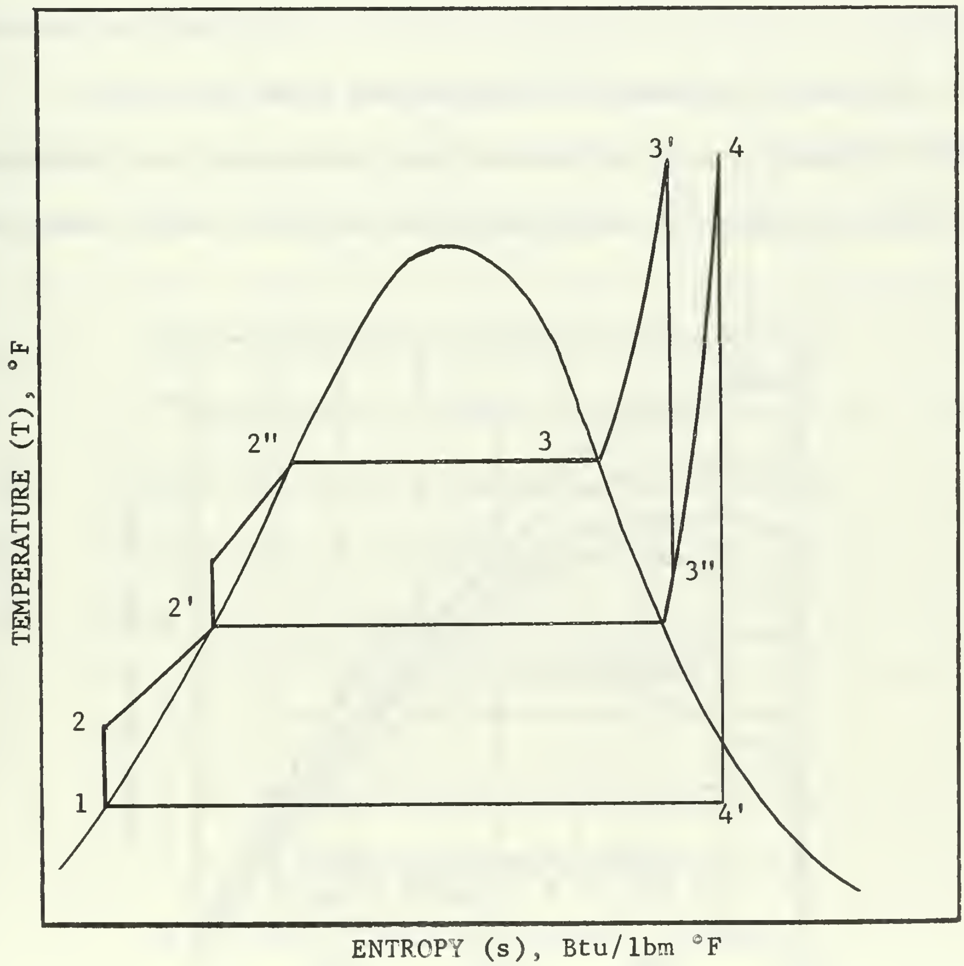


Figure 12. Ideal Rankine cycle with superheat, reheat, and regenerative heating.

External heat addition now only has to raise the temperature of the water from pt. 2' to pt. 2" instead of from pt. 2 to pt. 2". The average temperature of the external heat addition is thus increased, increasing the cycle thermal efficiency. Although Fig. 12 shows only one extraction for feedwater heating, a modern steam plant may employ several stages to gain improved efficiency. The number of stages used is purely an economic matter and although marked improvement in the plant heat rate may result from the addition of one or two heaters, diminishing returns are realized as additional heaters are added. The quantitative effects of regenerative heating on plant heat rate are illustrated in Fig. 13.

From the basic thermodynamic information presented, it can be concluded that the modern steam powerplant uses a complex thermodynamic power cycle. Various techniques such as superheat, reheat, and

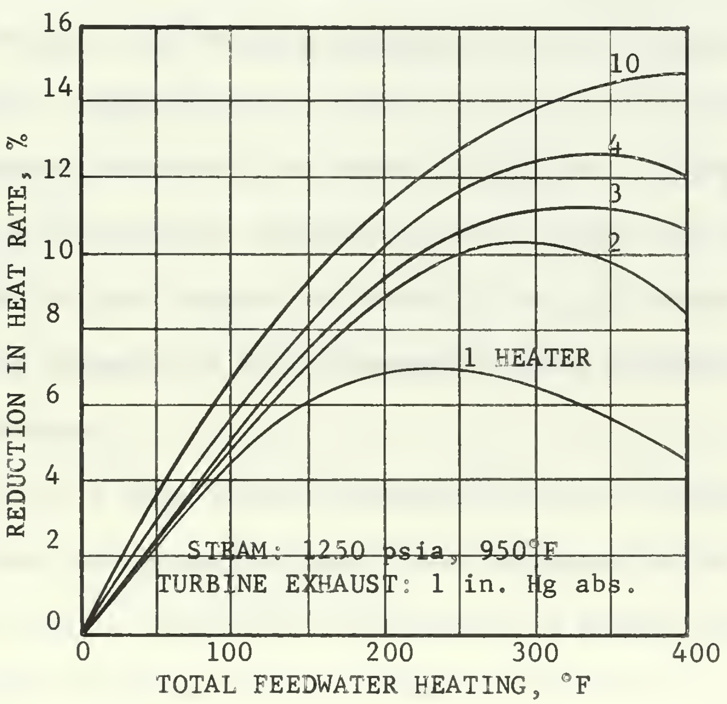


Figure 13. Effect of regenerative heating on powerplant heat rate (3).

regenerative heating are used to gain maximum plant thermal efficiency. Maximum plant thermal efficiency means minimum heat rejection, minimum thermal pollution, and minimum operating cost.

2.5 Thermodynamic Comparison of Two Modern Steam Powerplants

Using values taken from actual plant heat balance diagrams, a simplified thermodynamic analysis of two steam-electric powerplants - one nuclear, one fossil fuel (coal) - can be conducted to obtain typical values for heat rejection rates and thermal efficiencies.

A simplified T-s diagram for a Babcock and Wilcox pressurized water reactor plant with superheat is shown in Fig. 14. Mass flow rate changes due to extraction for regenerative heating are not accounted for on the diagram. The plant generates 11,368,367 lbm/hr of steam at 565°F, 885 psia and produces 915,286 kw of gross electrical power. It rejects heat at a condenser temperature of 91.7°F and a pressure of 1.5 inches Hg absolute. The cycle employs a small amount of superheat (35°F), six regenerative heating processes, moisture separation, and reheat (120°F). Calculations of total heat added, total heat rejected, and cycle thermal efficiency are shown in Appendix A using flow rates, pressures, and temperatures obtained from the plant heat balance diagram. The plant heat balance diagram was obtained through private communications with the Babcock and Wilcox Company's Power Generation Division at Lynchburg, Virginia.

Figure 15 is a simplified T-s diagram of the thermodynamic cycle used in the Bull Run Steam Station of the Tennessee Valley Authority (TVA). This plant is coal fired, operates at a supercritical pressure, and has a gross electrical output of 914,402 kw (79). The plant generates 6,335,200 lbm/hr of steam at 1000°F, 3515 psia and employs

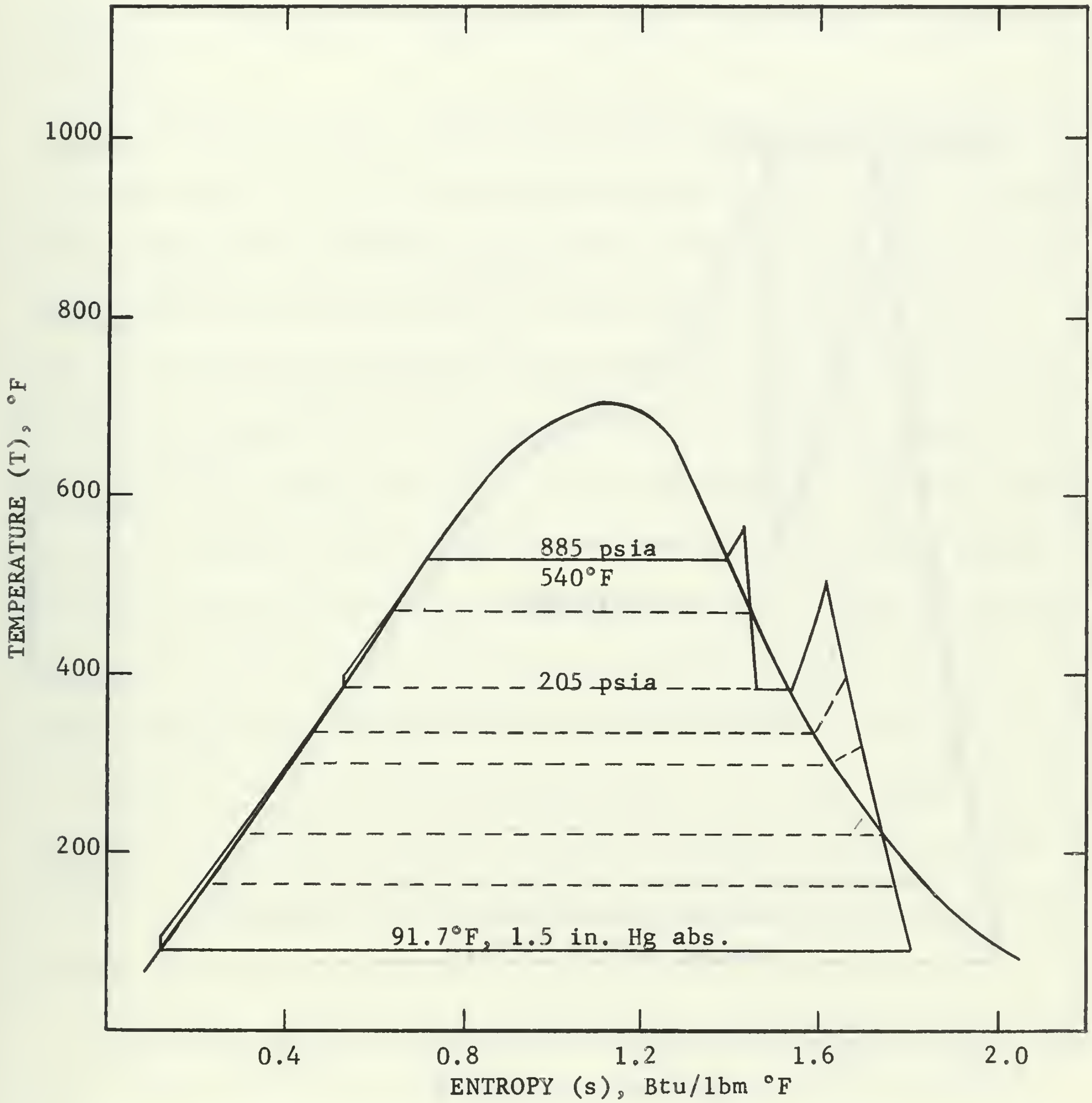


Figure 14. Babcock and Wilcox pressurized water, nuclear powerplant thermodynamic cycle.

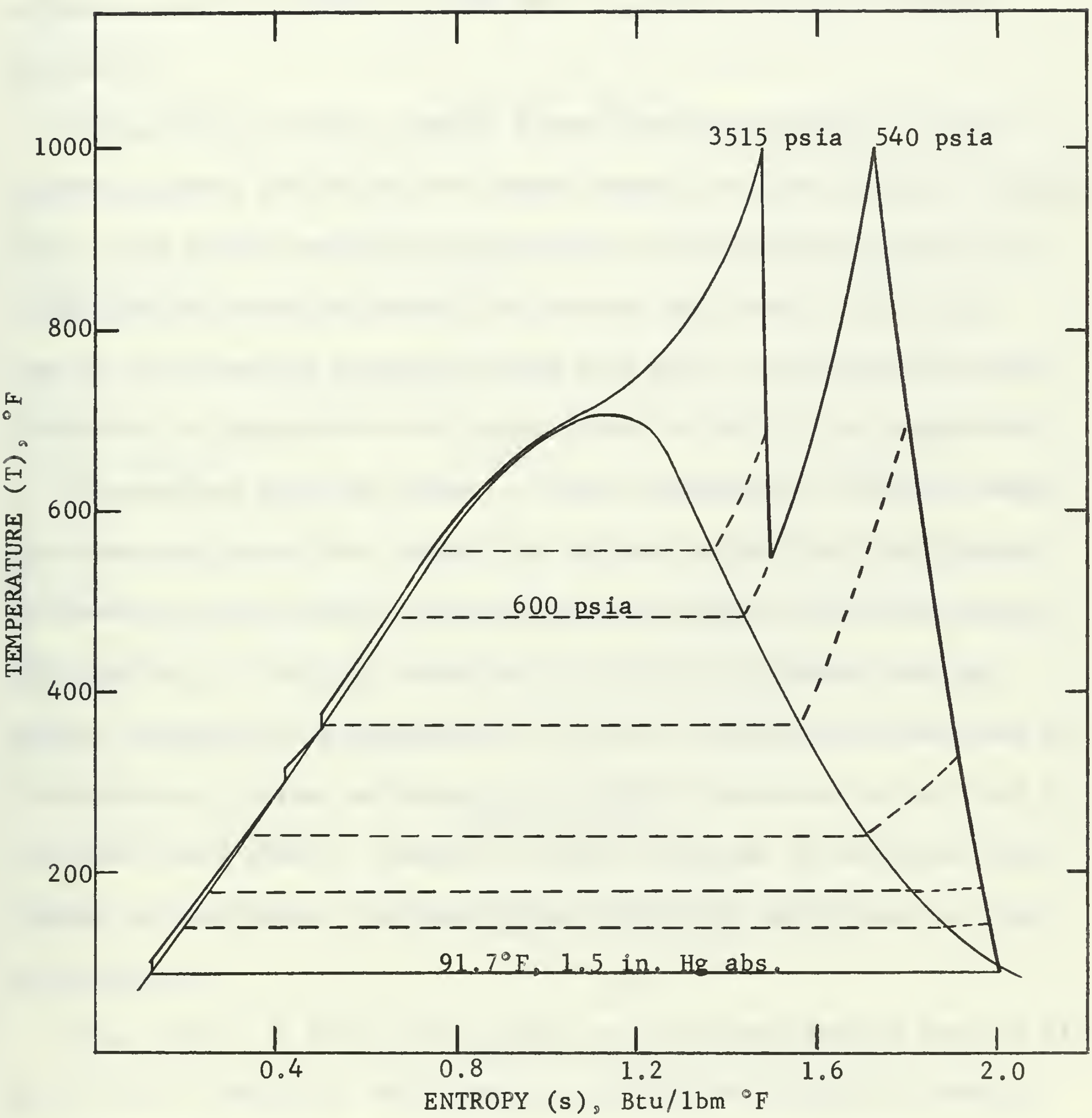


Figure 15. Bull Run Steam Station (TVA), coal-fired powerplant thermodynamic cycle.

reheat, six stages of regenerative heating, and supercritical superheat. Heat rejection in the condenser occurs at 91.7°F and 1.5 in. Hg absolute. Values of flow rates, temperatures, and pressures obtained from this plant's heat balance diagram (79) are used in Appendix B to calculate total heat added, total heat rejected, and cycle thermal efficiency.

Since the two plants produce almost identical amounts of gross electrical power and reject heat under exactly the same condenser conditions, they offer a meaningful comparison of the relative thermal pollution problem posed by present day nuclear and fossil fuel plants. Some of the important parameters from each plant, including the values calculated in Appendices A and B are listed in Table 1 for comparison.

The nuclear plant is found to reject approximately 56% more waste heat than the fossil fuel plant, for the same gross electrical output. The nuclear plant rejects 6700 Btu/kwhr; the fossil fuel plant rejects 4300 Btu/kwhr. From this comparison, it can be concluded that the nuclear steam-electric powerplants of current design contribute more to the problem of thermal pollution per kilowatt electrical output than do the fossil fuel plants. However, if heat rejection to the total environment is considered, the fossil fuel plant does not present as great an advantage.

The boilers in fossil fuel plants are non-ideal devices and not all of the heat produced by the combustion of fuel is utilized in making steam. Some of the heat is rejected to the atmosphere via the plants' exhaust, or stack. This rejected heat is called stack loss. A typical value for stack loss is 10% of the heat input of the fuel (3).

Table 1. Power Plant Parameters

Parameter	Nuclear Plant	Fossil-Fuel Plant
Gross electrical output	915,286 kw	914,402 kw
Plant thermal efficiency	32%	41%
Heat rejection to cooling water	$6.154 \cdot 10^9$ Btu/hr	$3.950 \cdot 10^9$ Btu/hr
Steam generation rate	11,368,367 lbm/hr	6,335,200 lbm/hr
Maximum steam temperature	565°F	1000°F
Maximum steam pressure	885 psia	3515 psia
Turbine exhaust temperature	91.7°F	91.7°F
Turbine exhaust pressure	1.5" Hg abs.	1.5" Hg abs.

Stack heat loss is expressed implicitly in the value for the plants' boiler efficiency as follows:

$$\text{Boiler efficiency} = 1 - \frac{\text{Stack heat loss}}{\text{Heat from fuel}}$$

or $$\text{Boiler efficiency} = \frac{\text{Heat utilized to produce steam}}{\text{Heat from fuel}}$$

Rearranging the two expressions above yields:

$$\text{Stack heat loss} = \left(\begin{array}{c}\text{Heat utilized to}\\ \text{produce steam}\end{array}\right)\left(\frac{1}{\text{Boiler efficiency}} - 1\right)$$

Assuming a typical boiler efficiency of 90% (3) for the TVA fossil fuel plant (Bull Run Station), the additional amount of heat it rejects to the atmosphere due to stack losses is found to be $740 \cdot 10^6$ Btu/hr. The total environmental heat load produced by each plant is then

$6.154 \cdot 10^9$ Btu/hr for the nuclear plant and $4.640 \cdot 10^9$ for the fossil fuel plant. These results show that the nuclear plant rejects only 31% more heat (and essentially no air pollution) when considering the total environment as opposed to 56% more heat when only thermal pollution of cooling water is considered.

The reason for the smaller heat rejection from the fossil fuel plant is that it can use a higher steam temperature and therefore operate at a greater thermal efficiency than the nuclear plant. The thermal cycle efficiencies were found to be 41% for the fossil fuel plant and 32% for the nuclear plant.

In summary, it may be stated that the quantity of waste heat produced by a steam-electric powerplant is a function of the size and thermal efficiency of the plant. Assuming a constant thermal efficiency, as the electric generating capacity of a plant is increased, its waste heat production increases. If the electric generating capacity of a powerplant is held constant and its thermal efficiency is increased, the amount of waste heat produced is decreased. Current design water cooled nuclear powerplants have lower average thermal efficiencies than the modern fossil fuel plants and therefore reject more waste heat to cooling water per kwhr of power produced.

III. THE EFFECT OF INCREASED WATER TEMPERATURE ON AQUATIC LIFE

Temperature is one of the most important and influential water quality characteristics to life in water and has been described as the ecological "master factor" (69). Other characteristics of water such as dissolved oxygen level and pH are functions of the temperature.

The delicate, complex ecological balance of the aquatic environment can be upset by just a small change in temperature with a resultant change in the behavior of all living parts of the ecosystem, from algae to game fish. The overall effect of a temperature change may be beneficial or harmful depending on the magnitude, rate, direction, and duration of the change.

3.1 Effects on Animal Life

Fresh water and marine biologists have found that aquatic organisms cannot live above or below certain temperature levels. Because thermal pollution causes an increase in water temperature, the effects of elevated, rather than low, temperatures will be emphasized.

3.1.1 Heat Death

Experiments have shown that, depending on the initial water temperature, a relatively small temperature increase - less than 10°F, may cause aquatic test animals to go from 0% to 100% mortalities (70). Under normal operating conditions, steam-electric powerplants heat condenser cooling water in excess of 10°F.

Direct, heat induced death in fish is thought to be a result of cell chemistry changes caused by the increased temperature. Some death mechanisms that have been postulated to occur because of increased temperature include melting of cell fats, coagulation of

cell proteins and toxic effects on cells by the products of increased metabolism (40).

A standard method of reporting the lethal temperature for an animal species is to specify the LD_{50} temperature, which is the temperature necessary to kill 50% of the test animals (70). The temperature dependence of mortality rate, and the variance of temperature tolerance from species to species are shown in Fig. 16. The estuarine species used as examples in Fig. 16 were acclimated to a temperature of about 15°C and then exposed to the various temperatures for 24 hours. The undesirable stinging sea nettle is seen to be most temperature tolerant of the species tested and has a LD_{50} temperature almost 20°F above the opossum shrimp (70).

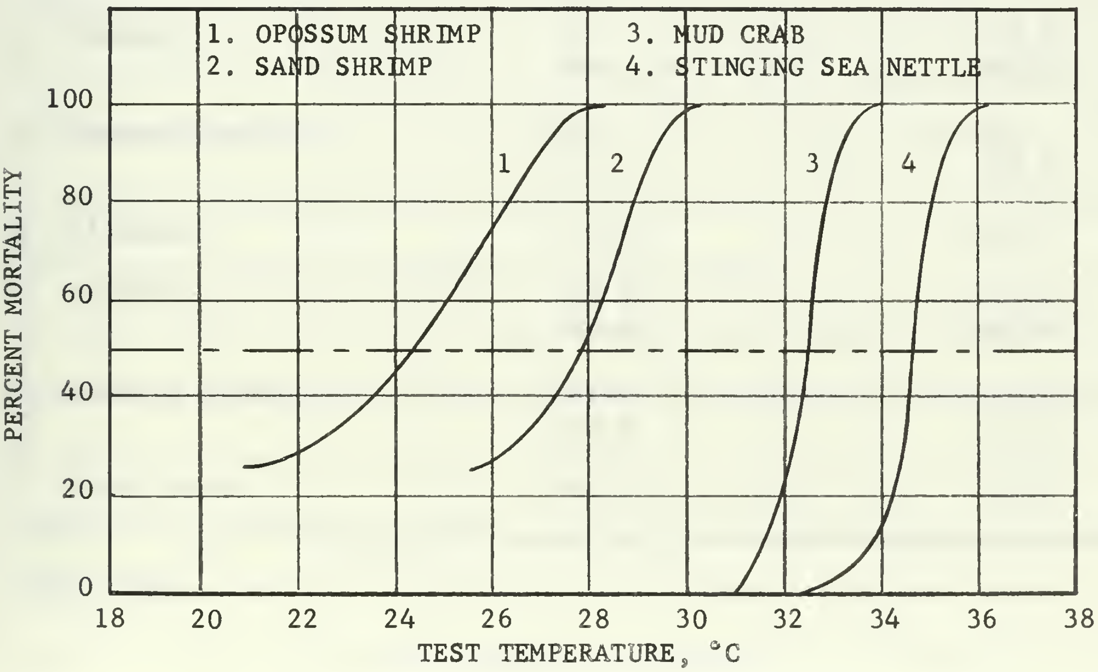


Figure 16. Comparative temperature mortality curves for four estuarine species (70).

Fish, as cold-blooded animals unable to regulate their body temperature, are also very sensitive to water temperature changes and their mortality rate as a function of temperature is similar to that of the animals illustrated in Fig. 16. The LD_{50} temperatures for some common fresh and salt water fish are given in Table 2. The high temperature tolerance of species such as the stinging sea nettle and the goldfish is indicative of the fact that higher water temperatures often favor the coarse and less desirable species (86). Most shellfish, such as clams, oysters, crabs, and lobsters are tolerant of a temperature range similar to fish.

Table 2. Tolerance Limits for Certain Fishes[a]

Fish	Acclimation Temperature (°F)	LD_{50} Temperature (°F)
1. Largemouth Bass	68	89.6
	86	93.2
2. Bluegill	59	87.8
	86	93.2
3. Channel Catfish	59	86
	77	93.2
4. Flounder	60.8	84.2
5. Goldfish	75.2	96.8
	98.6	107.6
6. Sockeye Salmon	41.0	72.0
	68.0	77.2
7. Brook Trout	68.0	77.0

[a] From (86).

3.1.2 Acclimation to Elevated Water Temperature

Fish and other aquatic organisms are physiologically adaptable and are able to acclimate to higher temperatures in relatively short times - a day or less; so that thermal pollution effects may be mitigated by the past thermal history of an individual fish or organism (112). Up to an eventual limit, increasing the acclimation temperature increases the upper limit of tolerance. Table 2 indicates the increase in LD_{50} temperature as acclimation temperature is increased. For example, experiments on goldfish have shown that if acclimated to 36°F, they could withstand temperatures up to 82.4°F; but if they were acclimated to 98.6°, the median tolerance level increased to 107.6°F (86). Acclimation also works in reverse in that fish acclimated to higher temperatures cannot withstand low temperatures which they readily tolerated before acclimation to the higher temperature. It also appears that acclimation to higher temperatures is more rapid than acclimation to lower temperatures (70). This fact implies that the effects of a shutdown of a steam-electric powerplant and the subsequent reduction in its cooling water temperature may be more detrimental than its normal operation with a constant discharge of heated water.

The rate of increase in temperature can be a lethal factor even though the LD_{50} temperature may not be exceeded. A lack of acclimation causes death by thermal shock if the temperature is changed abruptly. A temperature change of 10°F in ten minutes is considered to be the maximum rate of change that can be tolerated by most aquatic animals (51). A temperature transient of this rate and magnitude could occur at the cooling water discharge of a powerplant if a plant emergency developed requiring an immediate reduction of turbine generator

load. A rapid decrease in cooling water temperature would result from the rapid reduction in turbine load.

3.1.3 Indirect Effects of Elevated Water Temperature

Although heat can cause death directly by thermal shock or chemical changes in the cells, other indirect results of elevated temperatures usually are the lethal factor. Glooschenko (46) states that oxygen starvation is the main cause of thermally induced death in fishes and other aquatic organisms.

Clark (14) notes that metabolic processes generally double in rate for each 18°F rise in temperature and this increase in metabolism is accompanied by an increased rate of oxygen utilization. Oxygen consumption has been noted to quadruple in some fishes as temperature was raised to the lethal level. Laberge (59) reports that at low water temperatures in the range of 32°F to 39.2°F, a dissolved oxygen level of 1 to 2 mg/l is sufficient for the survival of many freshwater fish species. When the temperature reaches 59°F to 68°F, less than 3 mg/l of dissolved oxygen may be fatal and a level of greater than 5 mg/l is usually required by a fish species to enable it to perform normal activities such as food foraging. The problem of an increased oxygen demand is aggravated by the fact that oxygen is only slightly soluble in water. The saturation concentration of oxygen dissolved in water ranges from 10.15 mg/l at 59°F to 7.1 mg/l at 95°F (51). In addition, bacterial action and the natural purification process are accelerated as temperature increases, placing an additional demand on the oxygen supply. Therefore as the temperature rises and oxygen demand increases, the supply of dissolved oxygen decreases. As a further complication, the

hemoglobin in the blood of fish has a reduced affinity for oxygen at high temperatures (14).

The combination of dwindling oxygen supply, increased oxygen demand, and reduced oxygen utilization efficiency at elevated temperatures is the major cause of heat death in aquatic animals.

In addition to the hazard of direct heat death or oxygen starvation, a water temperature increase may increase the collective toxicity of other pollutants such as domestic sewage, insecticides, and fertilizers and lower a species' resistance to disease organisms. For instance, an 18°F rise in water temperature doubles the toxic effect of potassium cyanide on fish and fish kills have occurred with small temperature rises which may have been relatively harmless in an unpolluted stream free of toxic substances (40). Therefore, although the concentration of a substance may be harmless at one temperature, it may cause fish death when combined with the stress imposed by higher temperatures. Decreases in longevity and reduction in physical size of some aquatic animals have also been attributed to elevated water temperatures (14).

3.1.4 Modification of Life Processes

Although thermal shock and oxygen starvation are major hazards to aquatic life, thermal pollution can threaten the existance of a species in more subtle ways by modifying life processes.

Temperature plays a major role in the reporductive cycle of aquatic organisms. Most fish depend on a temperature increase to act as a signal to begin migration and spawning in the spring. In addition, the incubation period of fertilized fish eggs is temperature dependent and is generally shortened as the temperature increases (14). Therefore, the life cycle of a species could be upset by a sustained artificially

induced temperature increase since the young fish might hatch too early in the spring to find natural food. Water that is too warm may prevent the hatching of trout eggs and the spawning of salmon even though the temperature is not high enough to impair the life of the adult fish (98). This latter fact illustrates that temperature effects depend on the growth stage of an organism and are modified by the age and size of the organism, and by the season. For example, the temperature range for fish egg survival is narrower, particularly during the hatching process, than it is for other life stages; and reproduction is more restrictive in temperature requirements than is growth (70). Thermal pollution may prevent spawning if a thermal barrier of heated water is created in a river due to a power plant discharge. Anadromous (river spawning) fishes are generally very temperature sensitive and a thermal barrier could prevent their migration to proper spawning grounds (52).

The temperature requirements for the different life processes of a sockeye salmon are depicted graphically in Fig. 17. A thermal polygon has been drawn by plotting the upper and lower LD_{50} temperatures versus acclimation temperature. Inside of this polygon are two other polygons depicting the loading and inhibiting levels. In the temperature regime outside the loading level, an organism is required to expend more energy in performing normal life functions than it is able to replace, and activity and growth are impaired. The loading level is related to the difference between the rates of metabolism when an organism is at rest and when it is active. The inhibiting level depicted in Fig. 17 indicates the point beyond which temperature reduces a organism's ability to execute normal biological functions such as spawning, and thus inhibits chances of the species' survival.

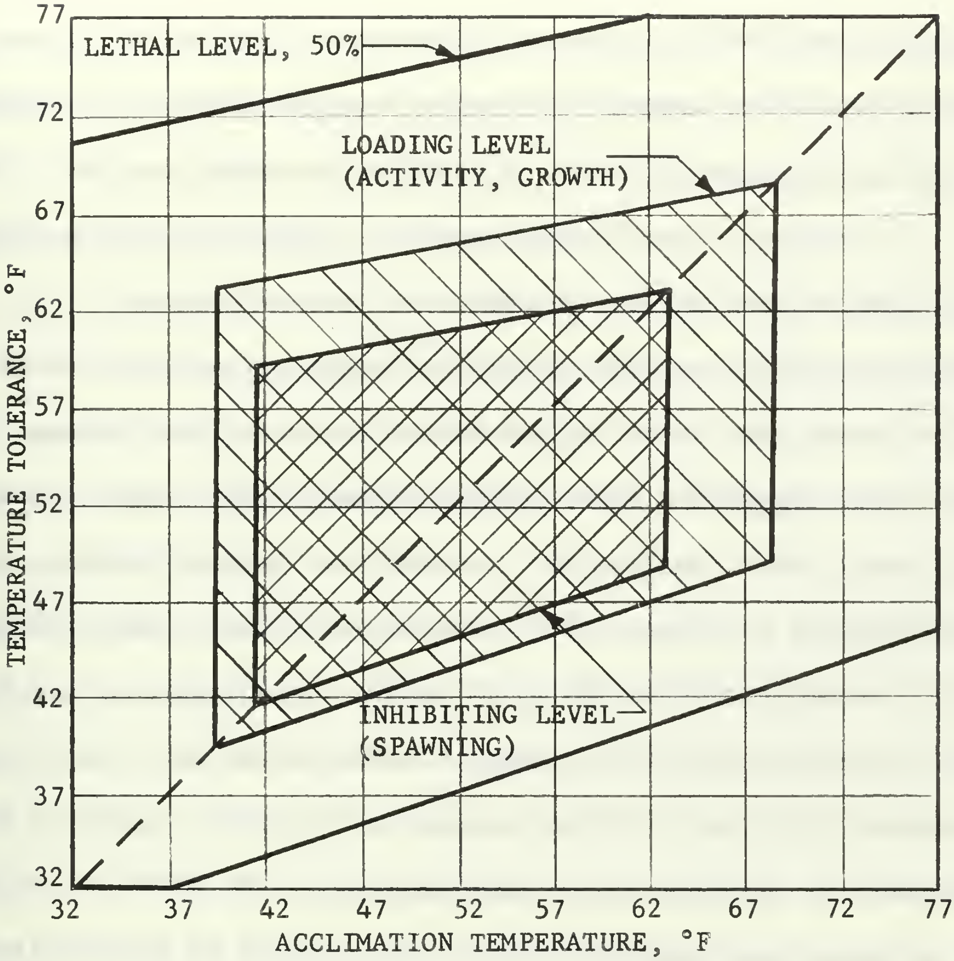


Figure 17. Thermal polygon showing temperature requirements for different life processes of a sockeye salmon (70).

Temperature influences activity by controlling the relative amounts of energy required for the basic metabolic functions such as respiration and for the performance of essential work such as food foraging. As temperature rises, the amount of energy required for basic metabolism increases while total available energy decreases or levels off. Therefore, the energy available for activity becomes less as temperature increases. If the ability of a fish to remain active is sufficiently curtailed, it may starve to death even if an abundance of food is available and the temperature is below the lethal level. As an example, brook trout, with an LD_{50} temperature of 77°F, were observed

to have their activity so curtailed in water at 70°F that they were incapable of catching minnows unless the minnows tails were clipped (86). The restriction of activity at elevated temperatures also renders a species more vulnerable to a more heat tolerant predator.

Unknown at this time are the effects that thermal pollution may have on vertically migrating species such as the opossum shrimp. This species remains on the bottom during the day and rises to the surface at night (70). Heated cooling water discharged from a power-plant normally remains in a layer at the surface. The effect on the opossum shrimp's behavioral pattern if it rises into abnormally warm water may be significant. Since it is the main food source for the striped bass, the entire aquatic population in the locale of a plant could be altered. Other food sources could be similarly affected. For example, in fresh water, insects make up the majority of invertebrates; and all species of insects that live in the water must come out of the water to complete their life cycle (100). An insect nymph in an artificially-warmed stream might emerge for mating too early in the spring and be immobilized by the low air temperature.

3.2 Effects on Plant Life

The ecological balance of an aquatic environment is equally as dependent on algae and other flora as it is on the animal life.

Phytoplankton - microscopic algae that produce food directly by photosynthesis, are the base of the aquatic food chain. Food production by phytoplankton is decreased by a temperature increase and the amount of food available to animal species is therefore lowered (46).

Zooplankton are microscopic animals that feed on phytoplankton and are the main food source for the higher aquatic animals. They are

generally not affected by thermal pollution. However, the grazing rates of zooplankton upon phytoplankton increase as temperature increases and since phytoplankton are adversely affected by a temperature rise, zooplankton may be affected indirectly (46).

Algae growth is normally stimulated by a moderate rise in temperature if there is an adequate supply of nutrients such as organic waste. This accelerated growth may result in "red tide" or other forms of undesirable algae blooms many of which produce foul odors, taste, and substances which may be toxic (14). In particular, blue-green algae are very heat resistant and appear to be an indicator of extreme thermal pollution as well as organic pollution (11). The change in the composition of the naturally occurring algae population with temperature is illustrated in Fig. 18. The indicated domination of the population by

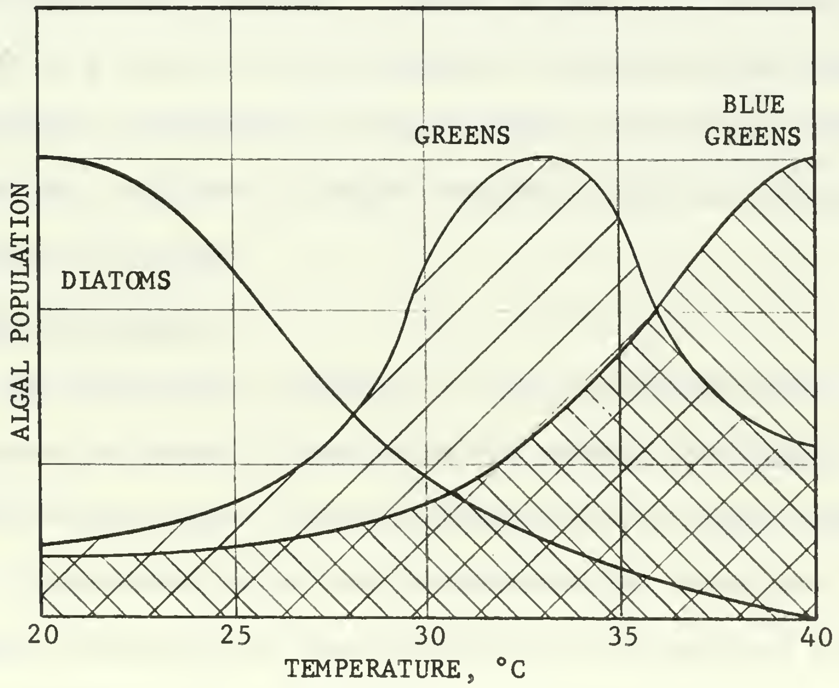


Figure 18. Algal population shifts with temperature (11).

blue-green algae at higher temperatures is undesirable since it causes a reduction in the oxygen supply in the water. Most aquatic plants give off oxygen during the daylight hours and consume oxygen during darkness with a net oxygen addition to the water over a 24 hour period (33). This cycle corresponds favorably with the level of oxygen solubility in the water which varies with the diurnal temperature changes. The temperature of the water is naturally higher in the daytime, due to solar heating, and oxygen solubility is reduced. However, because of the increased temperature during this period, the demand for oxygen by animal life is greatest. At this time, aquatic plants give off large amounts of oxygen maintaining the ecological balance. Blue-green algae are detrimental to this balance since they absorb oxygen from the water during the day as well as the night. Engle (33) reports on a biological survey downstream of a steam-electric powerplant on the Delaware River in Pennsylvania which indicated a marked increase in the growth of blue-green algae as a result of the discharge of heated cooling water. There was a concurrent suppression of normal growth of most other algae and this effect was noted over a length extending 2,500 feet downstream from the powerplant discharge.

3.3 Summary of Effects

From the information available, it can be concluded that the detrimental effects of thermal pollution on the aquatic environment, or even on a single animal species, cannot be measured by a single lethal temperature. Temperatures which can be tolerated for indefinite periods by an individual animal may be unsatisfactory for the survival of the species and ultimately be as harmful as outright heat death. Experiments performed on various fishes in their natural environment indicate

that the preferred temperature, at which adult fish thrive, averages 13°F below the lethal temperature for the species (14).

Of the thousands of aquatic plant and animal species known to exist in the inland waterways and coastal estuaries of the nation, only a small percentage have been specifically examined for their response to temperature. However, it has been demonstrated that many of these species will not be able to survive temperature increases much above those maxima that naturally occur and many desirable species may be severely damaged if there is excessive artificial heating.

IV. REMOVAL OF WASTE HEAT FROM STEAM POWERPLANTS

4.1 Cooling Water Requirements

The flow rate of cooling water required to remove a specified quantity of waste heat in a given time interval is inversely proportional to the amount of temperature increase of the cooling water permitted:

$$\dot{W} = \frac{Q_R}{C_p \Delta T}$$

where: $\dot{W}$ = cooling water flow rate (lbm/hr)

Q_R = heat rejection rate (Btu/hr)

C_p = specific heat of cooling water (Btu/lbm°F)

ΔT = cooling water temperature rise (°F)

The temperature rise of cooling water through condensers in existing powerplants generally ranges from 10°F to 30°F. Less than a 10°F rise is uncommon since a high flow rate is required and the cost of pumping the water becomes uneconomical. Greater than a 30°F rise is undesirable because of an increased fouling of condenser tubes due to a precipitation of calcium carbonate out of the cooling water.

Assuming a cooling water temperature rise of 20°F, the 915 MWe, B & W nuclear plant used as an example in the previous section of this paper is found to require 1370 ft^3/sec, or about 615,000 gallons per minute, of cooling water. This calculation is presented in Appendix C. The effect of cooling this single plant of about 900 MWe is equivalent to increasing the temperature by 20°F of an entire river, 50 feet wide, 9 feet deep and flowing at 3 feet per second.

In the past, enough water was supplied by nature in rivers, lakes, and other sources to be used on a once-through cooling basis. However, as plants approach and exceed 2000 MWe in size, fewer and fewer natural

sources can support the cooling water requirements. If an average circulating water requirement of 1.2 ft^3/sec per MWe is assumed (89), a 2000 MWe plant requires 2400 ft^3/sec of cooling water. Smith and Bovier (91) give the minimum natural surface water runoff as .5 ft^3/sec per square mile of drainage area. To allow adequate dilution of the discharged cooling water and thus minimize the amount of temperature rise in a river, it is desirable to withdraw as small a percentage of total river flow as possible for cooling water. A typical powerplant will withdraw 10%-25% of total river flow at conditions of minimum flow. Therefore, the resultant total cooling water requirement for a 2000 MWe plant calls for a river with a minimum flow of about 10,000 ft^3/sec and a drainage area of about 20,000 square miles. Only the major rivers in this country such as the Ohio, Missouri, Mississippi, Columbia, and possibly a few others, have a minimum flow equal to, or in excess of, the cooling water quantities required for once-through cooling of a plant of 2000 MWe or larger. In addition, growing public conern over the thermal pollution of waterways has led to an increased number of water conservation regulations and many states have placed into effect laws limiting water temperature rise. Therefore new powerplants may require onshore cooling systems even when built next to a source of water of adequate cooling capacity.

The once-through use of water from rivers, lakes, and oceans generally requires lower capital expenditures and lower operating costs than the use of recirculating water from cooling towers or other onshore cooling systems. However, the use of an onshore cooling system eliminates the need for location by large rivers, lakes, or the ocean, and permits a more optimum location with respect to fuel and distribution costs. An

example of this optimization of location are the mine-mouth coal burning powerplants which are located in the immediate vicinity of the coal mines supplying the fuel. For mine-mouth plants, the lower fuel costs may more than offset the added cost of an onshore cooling system and the increased cost of power transmission to load centers.

4.2 Once-Through Cooling

Once-through cooling is currently the most prevalent method of removing waste heat from powerplants. The cooling water is pumped from a water source, such as a river or lake, through the turbine condenser where it is heated by waste heat from the power cycle, and then discharged back to the water source from which it was withdrawn. The number of cooling water pumps in operation is changed as water intake temperatures seasonally increase or decrease, to maintain the desired condenser vacuum. It is not common practice to vary cooling water flow throughout a daily load cycle, hence load changes are reflected in a changing cooling water temperature rise across the condenser (24).

Observations of lake and reservoirs indicate that the water separates into three layers: epilimnion, thermocline, and hypolimnion. The epilimnion is the uppermost layer and has a relatively constant temperature with depth. In the thermocline, the middle layer, the temperature drops sharply with depth. The bottom layer, the hypolimnion, has only a minor drop in temperature with depth. Where once-through cooling uses water from a reservoir or lake, the practice has been to withdraw water from, and discharge to, the epilmnion. Measured data from existing installations indicates that the lower layer water temperature is relatively constant throughout the year, irrespective of heat loading or season (56). To take advantage of the lower water temperature,

hypolimnetic withdrawl is gaining favor in plant cooling, with intakes at depths up to 100 feet (29). There is a possibility that this practice may disturb the thermal stability of the lake or reservoir, or accelerate the natural eutrophication process. Concern over this aspect of thermal pollution has aroused considerable public opposition. A concise discussion of the possible consequences of hypolimnetic withdrawl for a nuclear powerplant on Cayuga Lake in New York State is given by Eipper et al. (29).

Whether the water source for once-through cooling is river, lake, or reservoir, the effluent is normally discharged near or on the surface of the receiving waterway. Since it is warmer and consequently less dense than the receiving water, the discharged cooling water spreads in a plume over the surface and is carried off in the direction of the prevailing surface currents. The subsequent dispersal of heat through the receiving water and into the atmosphere depends on a number of natural factors such as the speed of the water currents, turbulence of the receiving water, temperature difference between the water and the air, the humidity of the air, and the speed and direction of the wind.

To minimize the water temperature rise in a river caused by circulating water discharge, the minimum sustained river flow should be considerably more than the circulating water flow so that, by dilution, the average temperature of the river in the vicinity of and downstream of the plant will be reduced to acceptable levels. If the plant is located on an estuary or seacoast, it is minimum tidal flow which is important. As previously noted, a cooling water withdrawal rate equal to 10%-25% of minimum river flow is normal. Vermont Yankee Nuclear Power Corporation recently proposed a plan to withdraw an amount of cooling

water equal to approximately 2/3 of the minimum flow of the Connecticut River to cool their nuclear powerplant at Vernon, Vermont. It was estimated that during the summer months, discharging this amount of cooling water, heated by 20°F, back into the river would raise the temperature of the entire stream immediately downstream from the discharge by 13°F (15). This proposal aroused widespread public opposition and forced installation of a supplementary cooling tower system.

To prevent the recirculation of heated discharge to the intake and a subsequent increase in plant heat rejection temperature, intake and discharge must be well separated. Normally intake and discharge lines range from 200 to 300 feet each in length with an open discharge canal utilized to accomplish the necessary separation (102). Skimmer walls and underwater dams may also be utilized to prevent the effects of recirculation. McVay and Fiehn (68) note that a study for the Fort Martin Station of the Allegheny Power System indicated that the effect of recirculation would increase condenser inlet temperature by as much as 30 degrees above the normal river supply temperature and seriously curtail unit capability.

Although once-through cooling uses large amounts of water, it is largely a non-consumptive use. Less than one percent of the water used is lost by evaporative cooling downstream of the plant discharge (4). For a 1000 MWe plant the consumptive loss of water would be about 10,000 gpm. However, the quantity of water required, and the necessity of minimizing temperature rise in the waterways, limits the sites available for large, once-through cooled, powerplants. Therefore, onshore cooling systems must be considered.

4.3 Onshore Cooling Systems

The two main categories of onshore cooling systems are cooling ponds and cooling towers. With these systems, the cooling water is recirculated and its temperature is normally higher than the temperature of a natural waterway. This results in a higher plant heat rejection temperature and lower thermal efficiency than with a once-through cooling system. Onshore evaporative systems provide increased air-water contact as compared to the once-through system and about 75% of the heat is removed by evaporation; the remainder through conduction, convection and radiation. About 1000 Btu of heat is required to vaporize a pound of water. Most of this heat is taken from the water that remains and the water temperature is therefore reduced.

Since both cooling towers and cooling ponds depend largely on evaporative cooling (except dry towers, discussed later in para. 4.3.3.4), they consume from 50% to 100% more water than the once-through method.

A survey of proposed steam powerplants of 500 MWe or larger was recently conducted by the Energy Policy Staff of the President's Office of Science and Technology (36). It was estimated that by 1990, 492 of these large plants will be in operation and 158 of them, or 32%, will use onshore cooling systems. The staff of the Federal Water Pollution Control Administration, in reviewing the survey, suggests that the number of plants requiring onshore cooling may be greater than estimated as more states place further restrictions on water temperature increases.

4.3.1 Cooling Ponds

Cooling ponds are specially constructed artificial reservoirs which supply and receive the powerplant cooling water. The development of cooling ponds requires streams which are not polluted and

which may be either dammed completely or be subject to regulation of flow. These artificial ponds require a steady inflow of water to replace evaporation and bottom seepage losses and to prevent an excessive accumulation of dissolved material. Normal water supply is by natural runoff from the surrounding drainage area or by pumping from a stream of adequate makeup capacity. A potential source of makeup water for cooling ponds for plants near large cities is the effluent from municipal sewage treatment plants. This can be a constant and reliable supply. The drainage area necessary to support a cooling pond is dependent on the natural and forced evaporation rates and the amount of rainfall, but generally is about ten times the pond surface area (56). For a pond of the size required for a 1000 MWe plant, initial filling may take two or three years.

Heat rejection to cooling ponds presents a different problem from that of once-through cooling. The thermal energy balance for a cooling pond (or any open body of water) includes the following natural processes:

1. Evaporative heat loss
2. Long wave back radiation
3. Long wave atmospheric radiation
4. Short wave solar radiation
5. Conductive heat loss or gain
6. Reflected solar radiation
7. Atmospheric reflected radiation
8. Energy added to body of water by condensation, precipitation, and natural inflow
9. Energy removed from body of water by natural outflow

Heat transfer from a body of water to its containment, such as the soil, the river bottom, or the reservoir bottom is relatively insignificant. Typical values for the amount of heat transferred from the water surface by several of these processes are shown in Fig. 19. With no heating load, a pond surface reaches a thermal equilibrium temperature. However, when heat from a powerplant is added to the pond, a new equilibrium condition having higher energy and temperature levels is established, with the added, or forced, heat loss from the pond equal to the heat rejected by the plant to the cooling water. Weir and Brittain (111) give the following expressions for determining the forced heat loss from a unit area of a cooling pond by the different heat dissipation processes:

Heat loss due to forced radiation,

$$h_r = 1.10\ (t_h - t_n)\ \text{Btu/hr-ft}^2$$

Heat loss due to forced evaporation,

$$h_e = 13.0\ W(p_h - p_n)\ \text{Btu/hr-ft}^2$$

Heat loss due to forced conduction,

$$h_c = .132\ W(t_h - t_n)\ \text{Btu/hr-ft}^2$$

where t_h = temperature of heated water surface (°F)

t_n = natural temperature of water surface (°F)

W = wind speed at 26 ft. level (mph)

p_h = vapor pressure of saturated air at temperature t_h (in. Hg)

p_n = vapor pressure of saturated air at temperature t_n (in. Hg)

Steur (95) states that a typical value for evaporative water loss from a cooling pond due to plant heat load alone, is 6 feet of

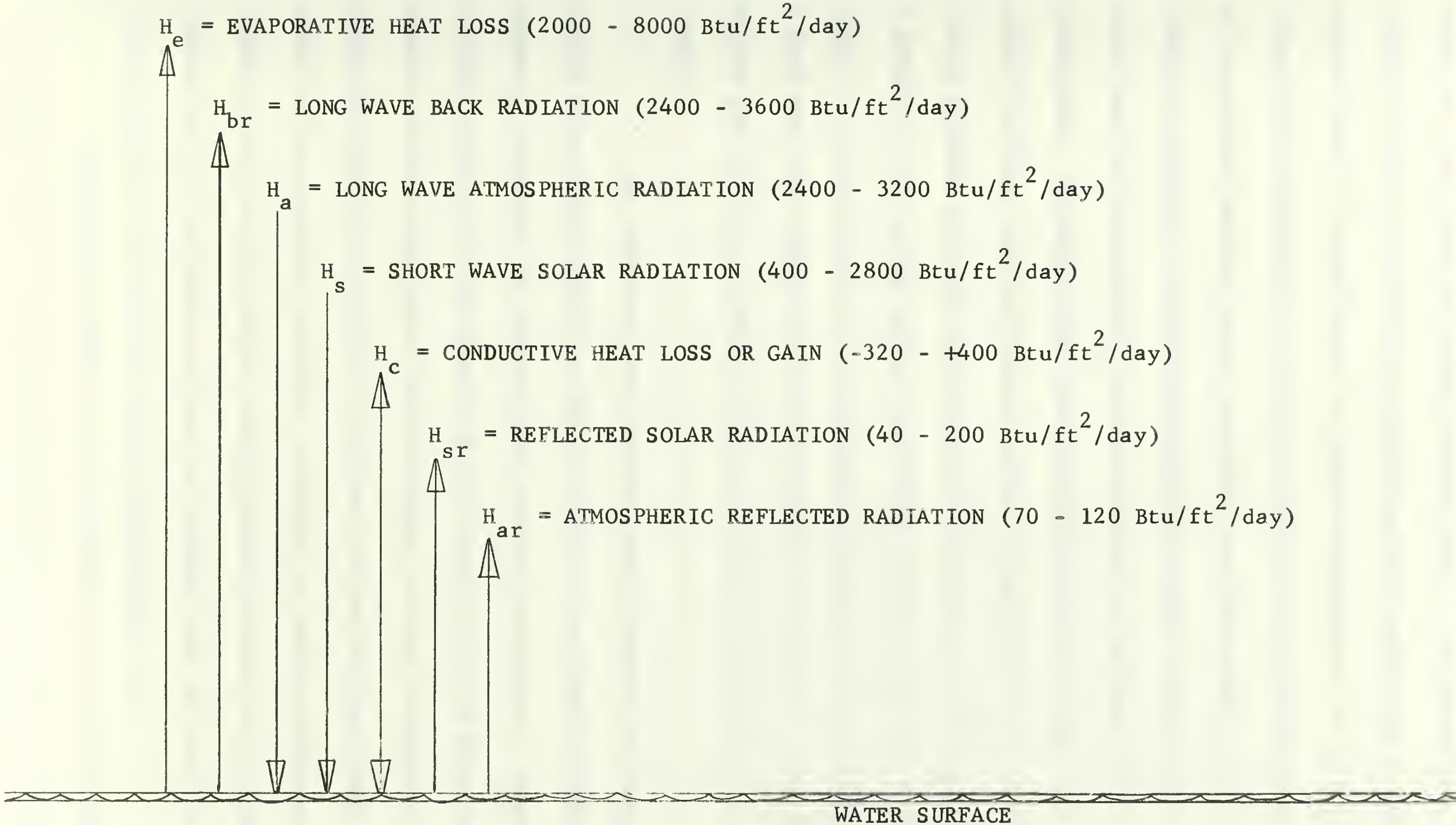


Figure 19. Mechanisms of heat transfer across a water surface (47).

water per year over the entire surface area. The water loss from a cooling pond due to natural evaporation will range from 2 feet to greater than 7 feet of water per year depending on the climatic conditions. The evaporation loss due to heat load is less than in the case of equivalent cooling towers because a pond dissipates some of the heat load by radiation. The total evaporation makeup requirements are dictated more by the climatic conditions than by the heat load from the powerplant. Although heat load evaporative loss is less with cooling ponds than with cooling towers, natural evaporative loss and loss due to bottom seepage from the pond generally result in a cooling pond having a greater total makeup water requirement than an equivalent cooling tower. A normal value for the makeup requirement to a cooling pond for a 1000 MWe plant might be 25,000 gallons per minute (as compared to 10,000 gpm for once-through cooling and about 20,000 gpm for cooling towers).

The effective pond surface area required for adequate cooling of circulating water can be as little as one acre per MWe of plant capacity, assuming an average plant thermal efficiency. McKelvey (67, p. 159) states that the area of a pond required for a given heating load is almost independent of pond depth; but that a depth of at least three feet appears advisable to prevent excessive channeling of flow in ponds having irregular bottoms. Although it would require a pond of infinite size for the heated cooling water to cool to the atmospheric temperature at the water surface, an average pond may cool the heated water to within 3°F to 4°F of this temperature.

Experience gained to date indicates that the configuration of the pond, which is normally determined by the natural terrain, seldom

permits equally effective utilization of the entire pond surface. Normally 1.5 acres, or more, gross area per MWe at maximum pond level is required (89). Therefore, for a plant of 1000 MWe, a cooling pond with a surface area of 1000 to 2000 acres would be required. A 2000 acre pond would be a mile wide and three miles long and require a natural drainage area of about 30 square miles.

Clark (14) describes the recommended design for a 2000 acre cooling pond for a 1000 MWe plant. The design calls for a reservoir only a few feet deep at one end and sloping to a depth of 50 feet at the other end. Water for cooling is withdrawn from about 30 feet below the surface at the deep end and is discharged 20°F hotter into the shallow end. The pumping rate for this particular plant is about 500,000 gallons per minute or 2000 acre-feet per day. All of the water of the pond (averaging 15 feet in depth) is turned over every 15 days.

The long, rectangular, shape of the pond just described is seldom practicable to obtain due to natural terrain. Therefore to minimize short circuiting of cooling water, baffles may have to be erected between intake and discharge structures if they cannot be separated as much as is required. Braswell (10) describes a cooling pond built for the 420 MWe Delta Station of the Mississippi Power and Light Co. The pond is 10 feet deep, covers 545 acres and has a central earth baffle 3500 feet long to prevent local recirculation. In the case of deep cooling ponds, it may be possible to obtain effective cooling with intake and discharge structures close together provided there can be sufficient vertical separation to take advantage of stratification of the water due to density differences. With this arrangement, the hot water discharged at the surface would tend to spread over the pond surface, while water

that has cooled and become denser would sink and flow toward the deep intake. Intake velocities must be low to prevent disturbance of the stratified flow.

In addition to the large amount of land required for adequate pond surface area for cooling, areas are required above the pond high water level for access and for the construction of a dam, spillway, and abutments. A proposed reservoir to store 25,000 acre-feet of cooling water makeup for a 1600 MWe plant requires a dam 85 feet high and 1100 feet wide (91).

In summary, the main advantages of cooling ponds are:

1. Simplest and cheapest method of onshore cooling.
2. May be operated for comparatively long periods without makeup (large storage capacity).
3. If contamination of the cooling water can occur, the pond serves as a retention and settling basin where the contaminant may be detected and removed.
4. May have recreational value (fishing, swimming, boating).

The disadvantages of cooling ponds are:

1. Inefficient compared to other methods of onshore cooling i.e., low heat transfer rate.
2. Large area needed.
3. Total water makeup requirements (including seepage) for a given heat load are generally greater than for a cooling tower.

The large area required is an indication of the difficulties involved in acquiring a cooling pond site for a large powerplant. If cooling pond sites or waterways capable of supplying once-through

cooling water are not available, then land requirements can be reduced by the use of spray ponds or cooling towers.

4.3.2 Spray Ponds

A spray pond is a cooling pond which introduces the warm cooling water through a spray system 5 to 8 feet above the water surface. The increased cooling surface area achieved by spraying the water into the pond increases the cooling efficiency per unit area of pond. McKelvey (67, p. 51) notes that this increased efficiency can reduce the pond surface area by a factor of 20 below that required for a cooling pond. The Canady Power Station, operated by South Carolina Electric and Gas Company, uses a 10 acre spray pond designed to cool 180,000 gpm from 101°F to 88°F - a total of 343 MW of heat removed (71). The cooling water is discharged to the pond through spray nozzles placed 5 feet above the reservoir surface. Each nozzle delivers 100 gpm at 7 psig internal pressure and sprays the water in a hemispherical pattern 10 feet into the air, the pattern expanding to a 24 foot diameter before reaching the pond surface. At full load operation, the active spray pattern covers an area of 150 by 1240 feet. The pond is 10 feet deep and the cooler water is withdrawn 4 feet below the surface. Scaling the characteristics of this pond to the size required for a 1000 MWe plant yields a spray pond size of about 70 acres.

The advantages of a spray pond are:

1. More efficient cooling than a cooling pond
2. Land requirements are reduced by a factor of about 20 compared to a cooling pond.
3. Generally less expensive to build and operate than cooling towers

The disadvantages of a spray pond are:

1. Larger land area required than for cooling towers
2. Generally more expensive to build and operate than a cooling pond
3. Nuisance created by spray if winds are strong i.e., fogging, icing of nearby roads

4.3.3 Cooling Towers

A cooling tower is an enclosed device which attempts to accelerate the natural cooling process. In the evaporative type, the water is sprayed onto a lattice network of wooden slats called "fill" and broken into droplets through which air is moved to cause evaporative and convective heat transfer. The cooled water is collected in a basin under the fill and pumped back to the condenser. In the dry cooling tower, heat is transferred indirectly by conduction and convection rather than by evaporation. The cooling water is pumped through finned tube cooler sections and air is circulated around the outside of the tubes to remove the heat. The closed system then returns the cooled water to the condenser. Dry cooling towers are identical in function to the common automobile radiator.

In addition to a tower being evaporative or dry, it may be further classified as mechanical draft or natural draft depending on whether fans are used to move the air through the tower.

4.3.3.1 Cooling Tower Terms

To aid in the discussion of the operation and characteristics of cooling towers, the following definitions are presented:

Dry-Bulb Temperature: (°F, °C) Temperature of air read on an ordinary thermometer, and the lowest temperature to which water can

be theoretically cooled in a dry cooling tower.

Wet-Bulb Temperature: (°F, °C) Temperature obtained by covering the bulb of an ordinary thermometer with wetted gauze and reading in moving air. It depends on the dryness and initial temperature of the air, but is lower than dry-bulb temperature because some water evaporates from the gauze, removing heat. The wet-bulb temperature is the theoretical limit to which water can be cooled through evaporation in an evaporative cooling tower.

Relative Humidity: (%) The ratio of the amount of water vapor actually present in the air to the greatest amount it could hold if saturated at that temperature and pressure. When the relative humidity is 100%, the wet-bulb temperature equals dry-bulb temperature. The lower the relative humidity, the greater the difference between wet-bulb and dry-bulb temperatures.

Cooling Range: (°F, °C) The number of degrees water is cooled in the tower. It is the temperature difference between hot water entering a tower and cold water leaving.

Approach: (°F, °C) The temperature difference between cold water leaving a tower and wet-bulb temperature of the surrounding air.

Drift, Carry-Over, or Windage Loss: Water carried out of a tower in mist or small droplet form by wind or air flow through the tower. It is usually expressed as a percentage of the circulating water flow rate.

Basin: The depressed portion of a tower beneath the cooling section used for collecting and storing cold water.

Blowdown: The continuous or intermittent discharge of a small portion of circulating water from the cooling system. It is usually

expressed as a percentage of the circulating water flow rate. It prevents build-up of dissolved solids left behind during evaporation.

Makeup: (gpm, cfs) Water required to replace normal system losses from evaporation, drift, blowdown, and leaks.

Packing or Fill: A lattice network of material placed in a tower over which water flows. It increases the air-water surface area and time of contact and maintains uniform air and water flow distribution.

Water Distribution System: A network of pipes which spreads incoming hot water uniformly over the packing in a tower.

Drift or Mist Eliminators: Baffles located above the water distribution system in a tower to prevent the loss of water from the tower. As air flows through the baffles in a curved path, entrained water particles are thrown from the airstream by centrifugal force.

Cell: The smallest basic integrated unit of a cooling tower installation. It normally consists of one fan and the necessary equipment to perform the cooling functions. Large installations consist of an integrated assembly of many cells.

4.3.3.2 Mechanical Draft Evaporative Towers

Mechanical draft evaporative towers currently predominate in the U. S. and are either crossflow or counterflow depending on whether the air flow crosses the path of the water flowing through the fill or whether the air flows vertically past the falling water in the opposite direction. A further classification is by the method air is moved through the tower. Air flow can be "forced," i.e., pushed through

the tower by a fan on the bottom, or "induced," i.e., pulled through the tower by a fan on the top.

Wood is the basic material of construction of mechanical draft towers. Redwood has been the most widely used because of its resistance to decay and because it maintains its structural configuration when subjected to large quantities of water at varying temperatures.

Some advantages of mechanical draft evaporative cooling towers are:

1. Cold water temperature can be closely controlled.
2. Small ground area requirement compared to a cooling pond or spray pond.
3. Generally low pumping head.
4. Location of tower is not restricted.
5. Close approach and long cooling range are possible.
6. Capital cost is less than for a natural draft tower.

Major disadvantages are:

1. Power requirements for fans results in high operating cost.
2. Subject to mechanical failure.
3. Maintenance costs are high.
4. May cause a noise and fog nuisance.
5. Climatic variations can affect performance because fans move a fixed volume of air regardless of its density and heat transfer properties. Wind may also affect performance adversely.

As discussed previously, the number of cooling water pumps may be adjusted to correct for seasonal variations in water temperature. Additional flexibility in controlling condenser temperature is available if mechanical draft cooling towers are used. The number of fans, or cooling tower cells, in use may be changed to adjust for diurnal and seasonal changes in water temperature.

A large majority of cooling towers currently in use are of the induced draft type. Air is drawn through the tower by fans located on top of the cell. The two classifications of induced draft towers differ in the direction of air flow in relation to the falling water. Figure 20 illustrates the crossflow type and Fig. 21, the counterflow type. Both types contain the same basic elements: a section where the air contacts the water - the fill or packing section, a section where mist is removed from the air leaving - the mist or draft eliminators, and the mechanical equipment used to move the air through the tower.

In the induced draft, crossflow, tower, heated cooling water is introduced into the tower through distribution basins at the top. The water flows by gravity from the basins through the fill, where it is cooled. The cooled water is collected in basins at the base of the tower and pumped back to the plant condensers. During each recirculative cycle between the plant and the cooling tower, about 2% to 3% of the volume of the cooling water is lost due to evaporation, draft, and blowdown. Air is pulled into the tower through louvered faces and flows horizontally through the fill section where it cools the fine water droplets falling perpendicularly to the air flow. The air then flows through the drift eliminators and is discharged vertically to the

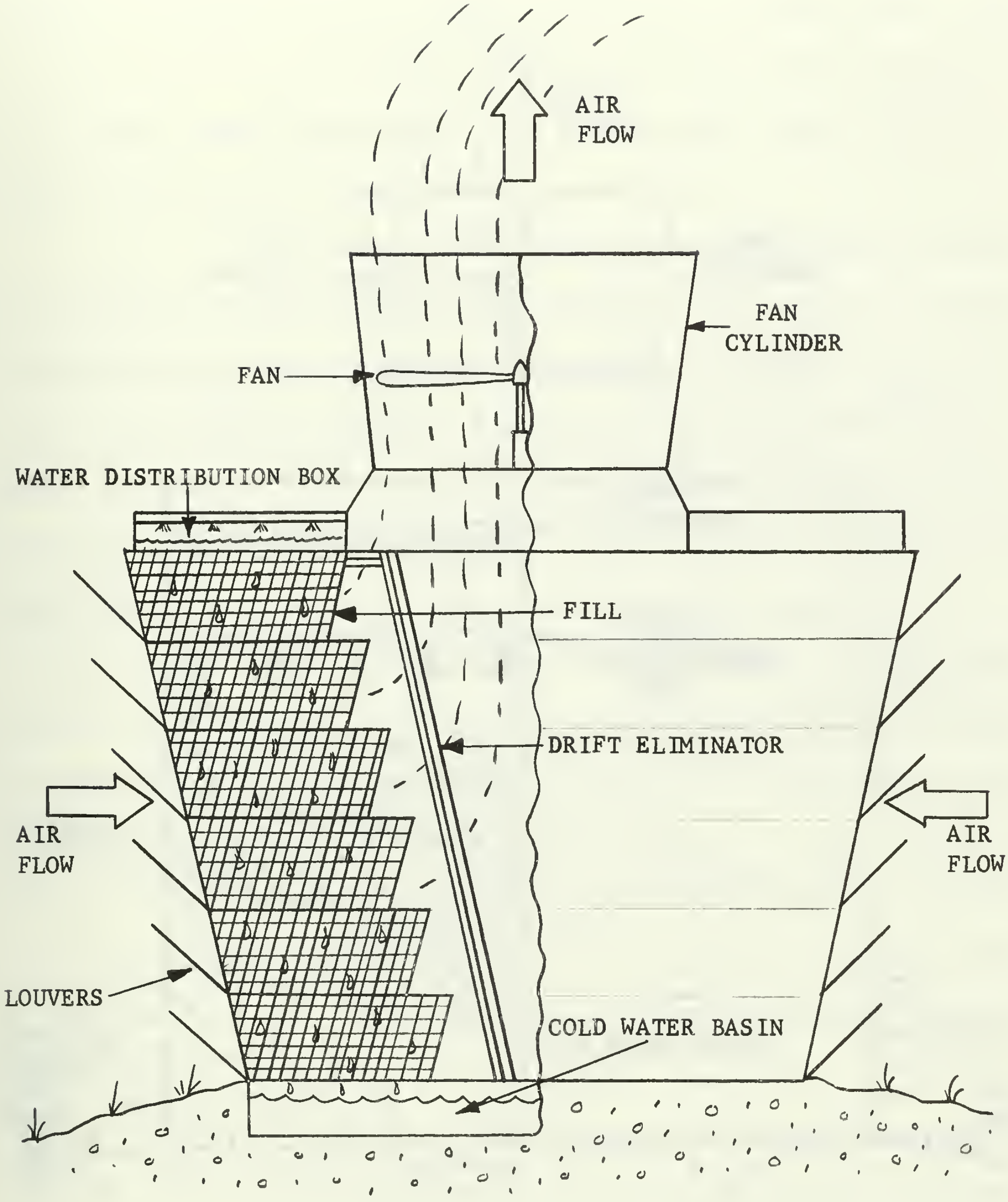


Figure 20. Induced draft, crossflow, evaporative cooling tower.

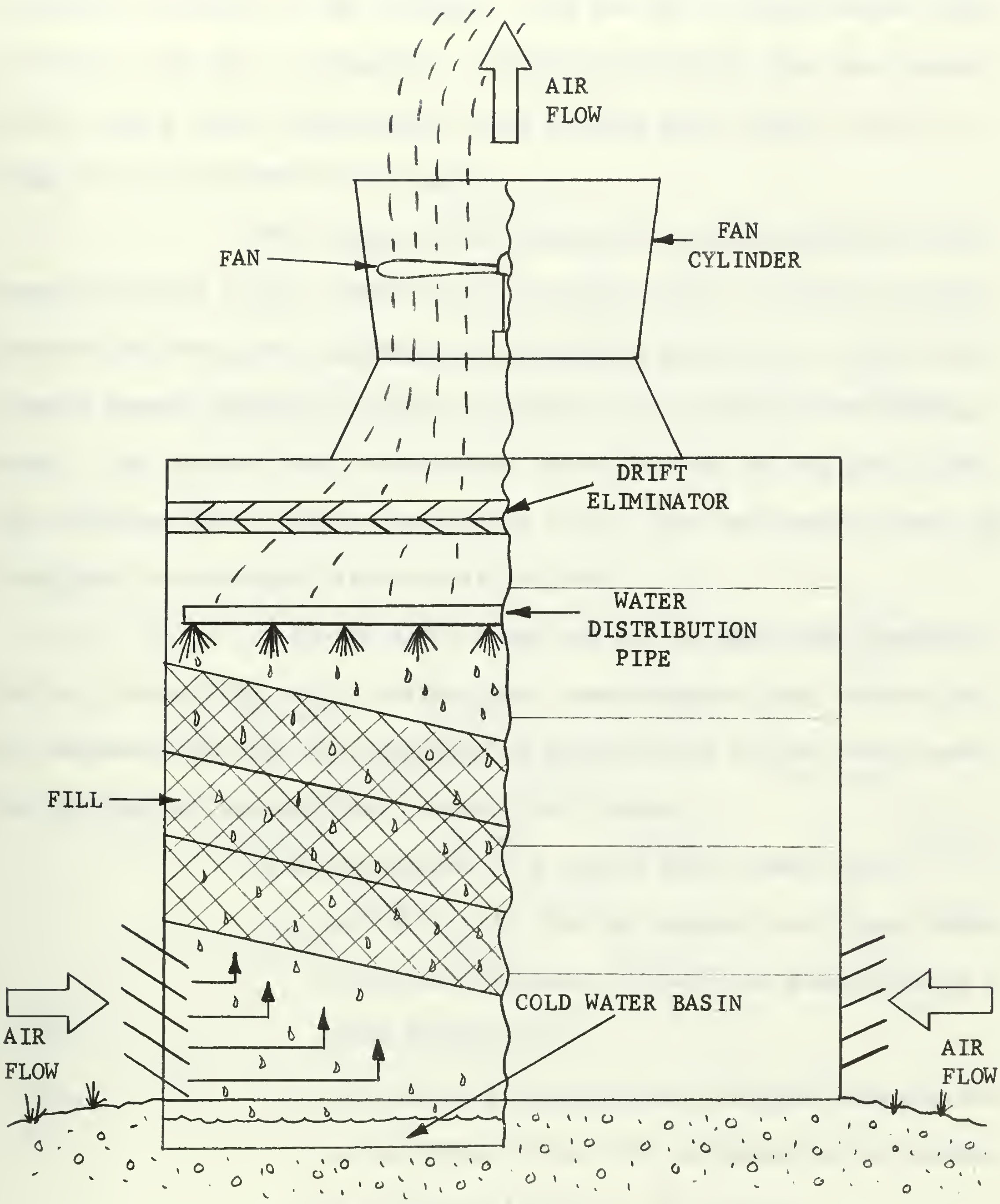


Figure 21. Induced draft, counterflow, evaporative cooling tower.

atmosphere through the fan cylinder. The fan for a large induced draft cell may be 60 feet in diameter. Kolflat (58) states that the induced draft cooling tower installation for a 500 MWe plant might be 600 ft. long, 70 ft. wide and 60 ft. high.

The induced draft counterflow tower operates on the same principles as the induced draft crossflow tower. However, in the counterflow tower, the incoming air is baffled such that it flows vertically upward through the tower - counter to the flow of the falling water. The induced draft counterflow tower, because of the additional air baffling, has a greater resistance to air flow and requires more fan power than a comparable size crossflow tower.

A forced draft tower has one or more fans located at the air intake (Fig. 22). Forced draft towers employ only counterflow air movement and with the exception of the position of the fans, operate the same as induced draft counterflow towers.

Some advantages of a forced draft tower are:

1. Less vibration than an induced draft tower since mechanical equipment is near the ground and on a solid foundation.
2. Less moisture condensation problems with the fans and gearboxes since this equipment is surrounded by a comparatively dry air stream.

Some of the disadvantages of the forced draft tower are:

1. The hot humid exhaust air can be drawn or recirculated back to the air intake.
2. Fan size is limited due to location in the tower

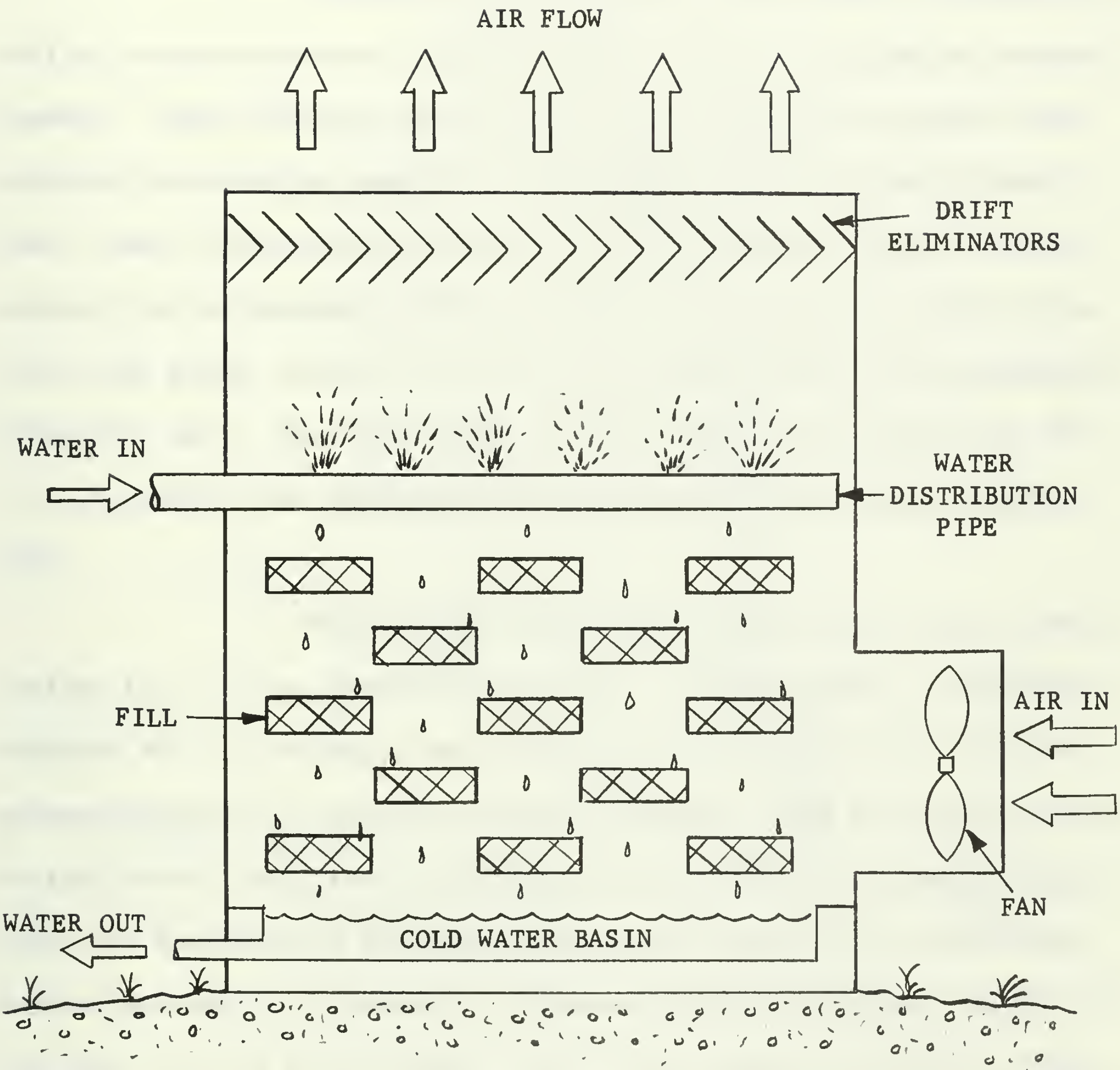


Figure 22. Forced draft, evaporative cooling tower (40).

which means more fans, motors, starters and wiring than are needed by induced draft towers.

4.3.3.3 Natural Draft Evaporative Towers

In England and in Europe, natural draft, evaporative cooling towers have been the most popular method of cooling for several decades. Lower European costs for labor and reinforced concrete (the preferred construction material), and higher costs for land (natural draft towers take up less space than mechanical draft towers) are the reasons for the European preference (85). The economy of scale of the new, large plants in the U. S. has only recently made them economically attractive here. The first tower of this type began operation in the U. S. in 1962 at the Big Sandy Station of the Kentucky Power Company (28).

Natural draft evaporative towers can be either counterflow (Fig. 23) or crossflow (Fig. 24). In both types, a hyperbolic concrete shell is normally used and serves as a chimney which has the primary function of creating a natural draft by using air heated by the cooling water. Air flow is created by the difference in density between the internal and external air and the necessity for using power for air movement is eliminated. External wind moving across the top of the tower can add to the amount of air flow through the tower by reducing the internal pressure creating a suction effect. Tower operation, however, is not dependent on wind flow.

McKelvey (67, p. 262) indicates that natural draft towers may have shapes other than hyperbolic including: cylindrical, conical, polygonal, or rectangular. The choice of shape is usually dictated by the desire to use a particular building material or by

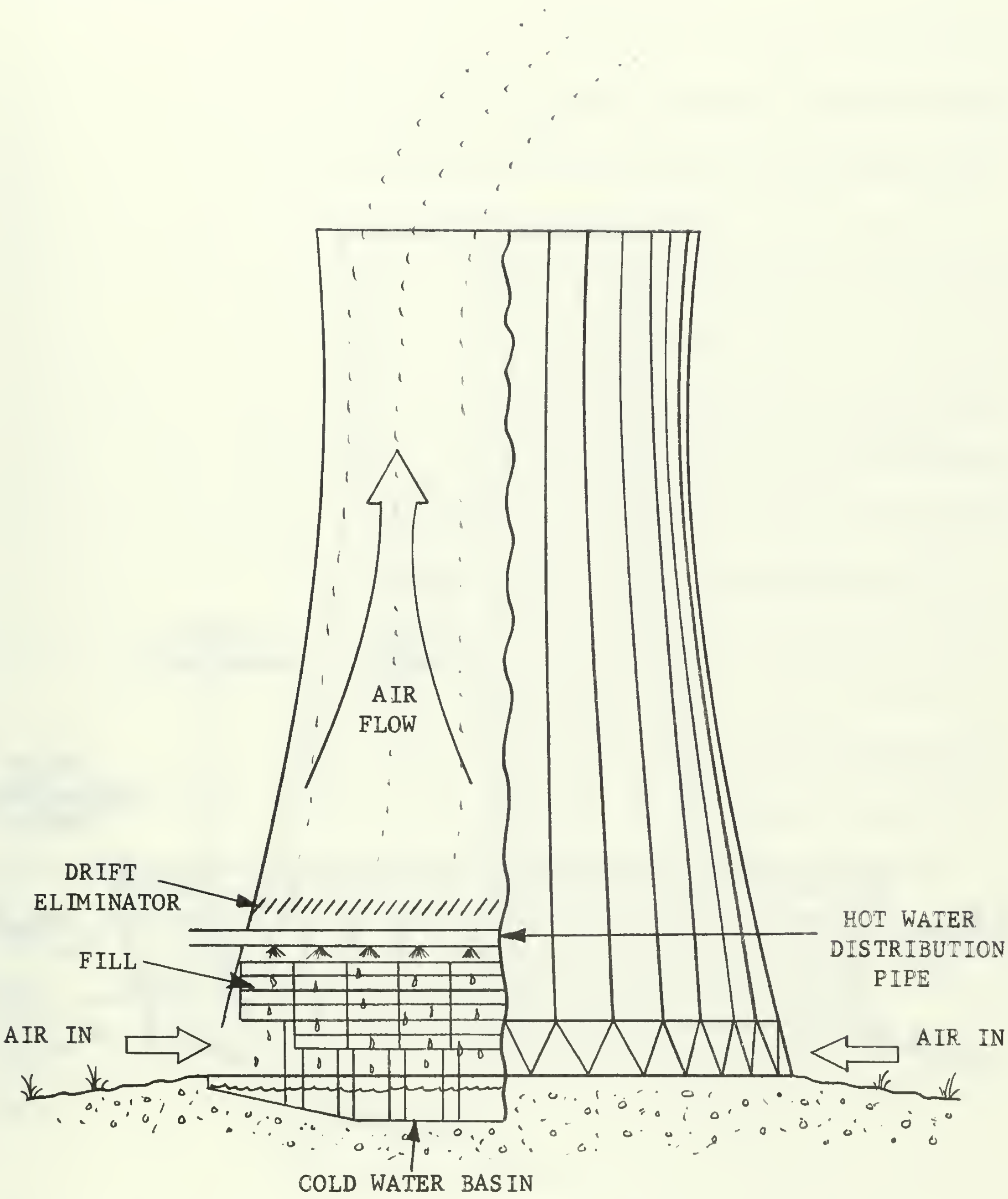


Figure 23. Natural draft, counterflow, evaporative cooling tower (40).

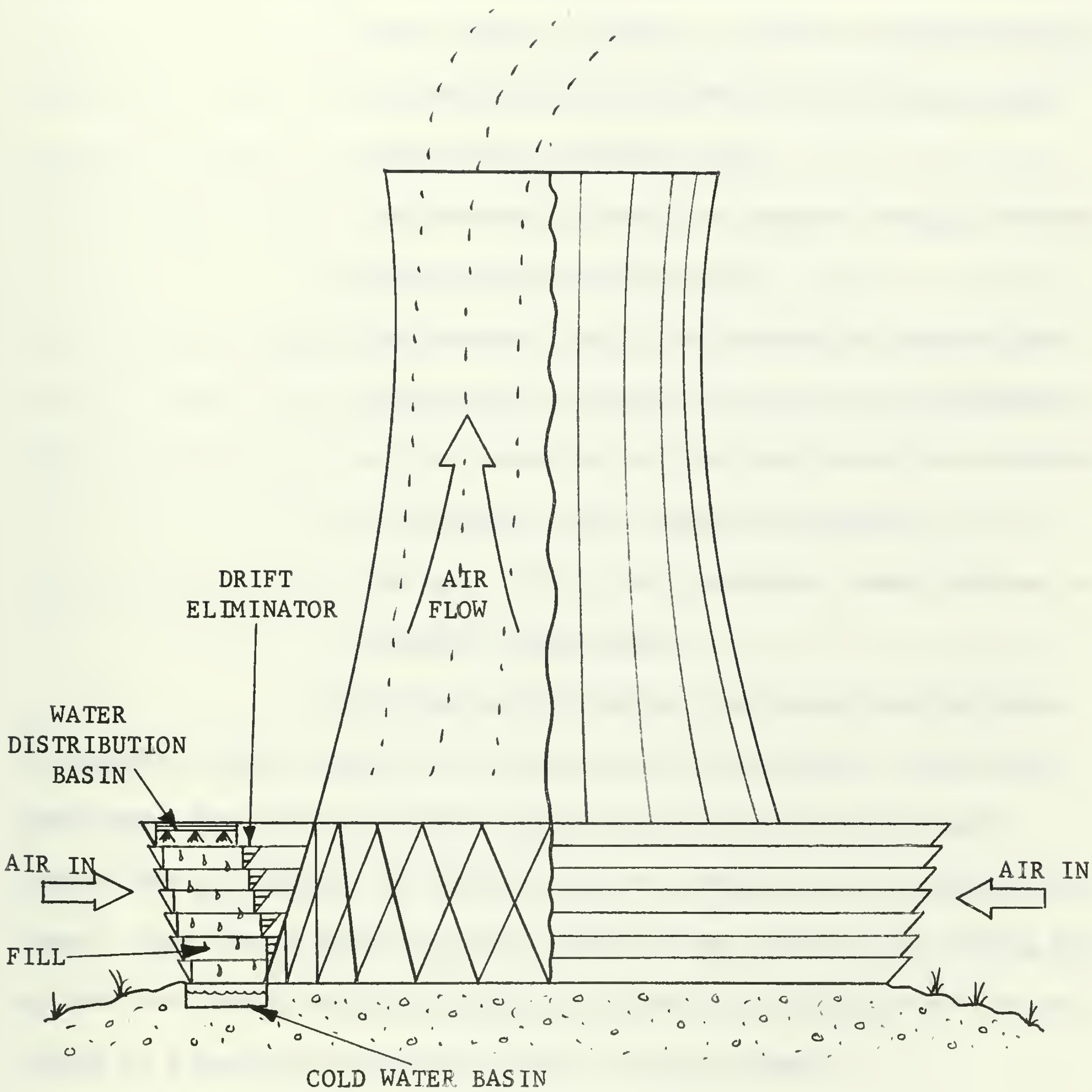


Figure 24. Natural draft, crossflow, evaporative cooling tower (40).

the expected external wind loading. Some of the advantages of the hyperbolic shape over the cylindrical shape include:

1. Since the cross section of the base of the hyperbolic tower is larger, a smaller entrance height is possible, for the same air intake area, and this saves in pumping head.
2. The hyperbolic tower has greater strength because of the doubly curved shell.
3. The enlarged top of the hyperbolic tower allows minute water droplets to fall out of suspension as the expanding airflow area causes the velocity to diminish. This reduces carryover.
4. The upper rim of the hyperbolic tower produces a stronger upward draft.

In the counterflow design, the heated cooling water is sprayed on fill placed in the lower part of the shell. This heated water warms the air in the fill region and saturates it with water vapor. The air density is decreased by this process and it rises up the tower. Cool air is drawn into the bottom of the tower by the rising hot air and continuous natural circulation occurs. The cooled water is collected in a basin which extends under the entire tower.

The crossflow design has the fill located around the outer periphery of the shell and the cold water basin only under the fill. Air is heated in the same manner as in the counterflow tower but incoming air flows horizontally through the falling water and then rises up through the empty tower shell.

The physical size and capacity of natural draft

towers is enormous. McVay and Fiehn (68) describe the towers for the 1080 MWe Fort Martin Station of the Allegheny Power System. This plant utilizes two natural draft, crossflow, evaporative towers. Each tower is 370 ft. high, 378 ft. in diameter, and capable of cooling 250,000 gpm from 114°F to 90°F. There are towers larger than these in operation. Hansen and Parker (48) state that there are single towers which can handle cooling-water requirements for 1000 MWe units.

Remirez (85) notes that the construction of natural draft towers requires soil with a bearing capacity of 4000 lb/ft^2 or greater. This requirement can be met in most areas of the U. S. except along the Gulf Coast.

The main advantages of natural draft evaporative towers are:

1. They can perform the same amount of cooling as mechanical draft towers without the mechanical parts and the power required to run them.
2. Negligable maintenance requirements.
3. They have a large cooling water flow capacity.
4. They avoid the ground fog nuisance by discharging the moist heated air at a great height. There are no fans to cause a noise nuisance.

The main disadvantages are:

1. Must have minimum internal resistance to air flow.
2. Large shell heights are required to produce an adequate air flow. This may be aesthetically undesirable.

3. Exact control of outlet water temperature is difficult to achieve.
4. Inlet hot water temperature must be higher than the air dry-bulb temperature to induce air flow.

Davidson (19) describes a recent innovation on the natural draft evaporative tower that has been developed by the Central Electricity Generating Board in Britain - the "assisted" draft tower. A large (450 ft. diameter, 375 ft. high) hyperbolic shell is used; but around the base the tower has 30 cells each fitted with a 26 ft. diameter fan, crossflow fill, and a mist eliminator. An annular basin below the cells collects the cooling water. The fans for this unit require 2 to 3 MW of power and the unit is capable of cooling 660 MW. This is double the cooling capacity of the tower without fans.

4.3.3.4 Dry Cooling Towers

In the dry cooling tower, indirect heat transfer from the cooling water to the air occurs by conduction and convection through finned tubes instead of by evaporation. There is no evaporative water loss but greater air movement is necessary than with evaporative towers. Brady and Geyer (9) state that the rate of flow of dry air needed to carry away the waste heat from a 2000 MWe plant, assuming a 20°F rise in air temperature, is about 10 million cubic feet per second. The dry tower's cold water temperature approaches the dry bulb rather than the wet bulb temperature which is usually lower, especially in summer. Therefore the cooled water is warmer than from an evaporative tower. Accordingly the water is normally introduced into a direct contact jet condenser to keep the plant heat rejection temperature as low as possible (80).

Dry towers may be natural draft or mechanical draft. A dry, induced draft tower is depicted in Fig. 25. Mechanical draft, dry towers have finned-tube coil sections mounted horizontally below fans which draw air over the tubes to cool the water flowing in them. Kolflat (58) gives the size of a typical fan section, or cell, as about 20 ft. square and estimates that 660 sections might be necessary for a 500 MWe unit.

Natural draft, dry towers have finned-tube coil sections mounted vertically around the base of a hyperbolic chimney shell. For the same cooling capacity, the shell must be of much greater diameter than for the natural draft evaporative tower because four to five times more air must be moved.

The Rugely Station of the Central Electricity Generating Board in Great Britain was the first powerplant to use a dry cooling tower. The tower is a hyperbolic, natural draft installation and the heat exchanger consists of 216 panels, 45 feet high, on a zig-zag pattern around the tower base. Each heat-exchange panel has three aluminum radiators very similar to automobile radiators (19).

The cooling water cycle for this plant differs from the normal installation. The cooling water, which is of condensate purity, is sprayed into a jet condenser to condense the exhaust steam. The mixture of condensate and cooling water is pumped from the condenser by large pumps. A portion of this mixture is returned to the boiler via the feedwater heating system. The majority of the mixture is sent to the air-cooled heat exchangers where it is cooled before returning to the condenser through the spray jets. A positive head is maintained on the cooling water system to prevent air leakage. The mixing of the

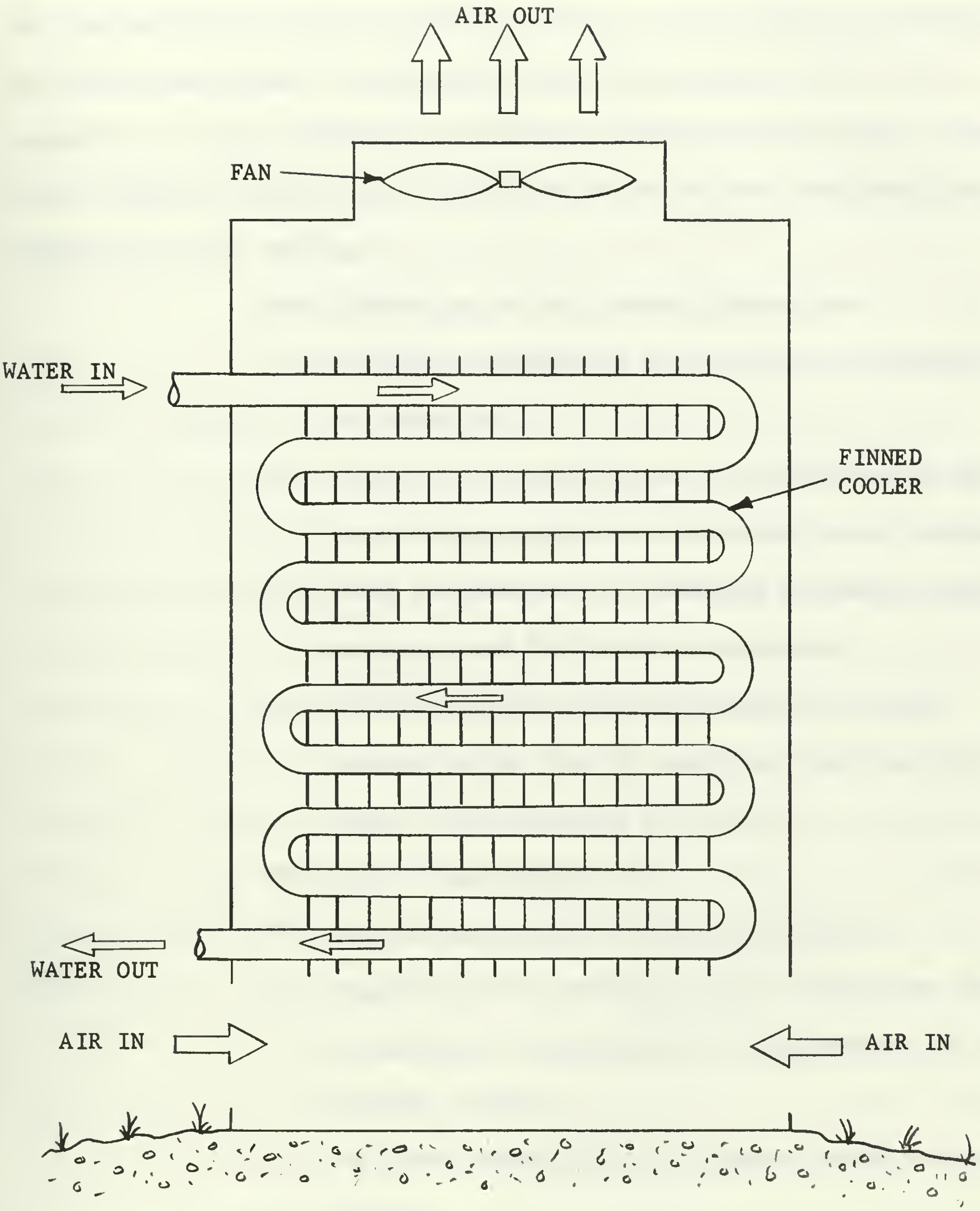


Figure 25. Induced draft, dry cooling tower (40).

condensate and cooling water in the jet condenser is permissible since the cooling water is never exposed to the air. This feature eliminates the difference between cooling water outlet temperature and condenser temperature thereby improving the thermal efficiency of the cycle. However, condenser temperature is still not as low as that attainable using evaporative tower cooling.

Some advantages of dry cooling towers are:

1. Low water consumption since makeup requirements are negligable.
2. Plant site location is not as restricted as with once-through, pond, or evaporative tower cooling.
3. Water problems such as chemical treatment, spray nuisance, and fouling are eliminated.
4. Cooling capacity can be increased to a much greater extent than is possible with evaporative towers (by increasing air flow).

The major disadvantages are:

1. Much higher capital and operating cost.
2. Theoretical and practical lower temperature limit of cooling is higher than for evaporative or once-through cooling.
3. The large amount of fans required create a noise problem.

4.3.3.5 Side Effects of Cooling Towers

With the exception of the dry towers, all of the cooling towers discussed previously can provoke a continuous precipitation of drizzle in their neighborhood. The most objectionable

consequences of this drizzle are an aggravation of the corrosion of steelwork in surrounding buildings and a public nuisance. McKelvey (67, p. 189) cites the principle causes of drizzle formation as:

1. Condensation of the moisture evaporated in the tower when the warm exit air meets the cooler atmospheric air.
2. Carryover, i.e., water droplets entrained by the air flow through the tower.

However, atmospheric conditions suitable for producing drizzle at ground level due to condensation are such extreme cases that they are not often encountered in practice. McKelvey reports that a survey of five operating cooling tower installations showed drizzle from condensation is more a rarety than a likelihood and is due mainly to faulty tower design. Carryover is found to be the most probable cause of drizzle. The Federal Water Pollution Control Administration's "Industrial Waste Guide on Thermal Pollution" (40) indicates that natural draft towers do not produce ground level drizzle under any weather conditions and for mechanical draft towers the sensible drizzle is localized to within about 300 feet of the tower.

Because of this fine spray carryover from towers, their use is essentially ruled out where salt water is a coolant. The salt spray ejected from a tower as carryover could destroy vegetation and otherwise foul the environment over a large area surrounding the tower.

Another nuisance that may result from cooling towers is fog. Berman (5) states that in winter, dense fog can occur around mechanical draft evaporative towers and up to one quarter mile away on

the leeward side. Ice may form on buildings up to 500 feet away. Because of the great height of natural draft towers, ground level fogging is not a problem with them.

Noise from fans may be another problem with mechanical draft towers. Estcourt (34) reports that the Pacific Gas and Electric Co. erected a sound barrier at their Martinez Station to reduce the fan noise in the area surrounding the cooling towers.

The cooling water used in a cooling tower system is normally chemically treated to prevent corrosion and scaling of condenser tubes, and to inhibit biological growth. The discharge of this chemically treated water as blowdown may have an adverse effect on aquatic life if not properly diluted or treated. However, the use of treatment chemicals known to have a toxic effect has been decreasing.

4.3.4 Comparative Performance and Features of Onshore Cooling Systems

For average heat loading, the performance of cooling towers and ponds is comparable. Under peak temperature and loading conditions, the cooling pond usually gives better cooling (a longer range). In addition, the cooling pond has a much greater inertia effect than a tower and therefore reacts more slowly to changes in atmospheric air temperature or heat input.

The ground area required may be a deciding factor in plant siting or cooling system selection, in areas where land costs are high or where large areas of land are not available. A comparison of the relative ground areas required by the various types of onshore cooling systems with the same heat load is given below, from McKelvey (67, p. 51):

System	Relative Land Area
Cooling Pond	1000
Spray Pond	50
Cooling Towers	1-2

Hyperbolic evaporative towers require much less ground area than do mechanical draft towers, which require additional area to minimize air recirculation. Natural draft towers can be located on centers one and one-half times the tower base diameter.

In other respects, the differences in characteristics between cooling towers and cooling ponds may be summarized as follows:

1. Maintenance costs and time are greater for a cooling tower.
2. If land costs are low, the capital cost of a cooling pond is less than for a cooling tower installation.
3. Mechanical draft cooling towers may cause a noise nuisance.
4. Cooling ponds have a much longer life than cooling towers.
5. Fog or vapor problems can be expected most frequently from mechanical draft evaporative towers and spray ponds, moderately from cooling ponds, and none from natural draft evaporative towers or dry towers.
6. Both the mechanical draft and natural draft towers have an auxiliary power requirement higher than that of the cooling or spray ponds. This is because the cooling water must be pumped to an elevation above the base of the tower, which may range from 20 to 35 feet. The

mechanical draft tower has an additional power requirement for its fans.

7. The makeup water requirements for the cooling tower are greater than that of the cooling pond for the same heat dissipation. However, the additional water losses from natural evaporation and seepage can make the total makeup requirement for a pond much higher than for a cooling tower. Typical total makeup requirements, in percent of cooling water flow rate are 4% for cooling ponds and 2.5% for cooling towers. In more explicit terms, a 1000 MWe plant with cooling towers would require about 20,000 gpm of makeup water. This quantity of water is equivalent to the municipal water supply for a city of over 250,000 people.

To illustrate the relative performance characteristics of dry and evaporative cooling towers, the approximate optimum cooling range and approach of the four major classifications of towers are listed below (58):

Type of Cooling Tower	Optimum Range	Optimum Approach
Mechanical Draft Evaporative	21°F	18°F
Natural Draft Evaporative	26°F	18°F
Mechanical Draft Dry	12°F	33°F
Natural Draft Dry	17°F	38°F

A comparison of the total auxilary power requirements for various cooling systems is tabulated below, from information given by Kolflat (58):

Cooling Systems	Auxiliary Power Required, % of generator output
Once-Through, Cooling Ponds, Spray Ponds	0.5 %
Natural Draft Evaporative Towers	0.75%
Natural Draft Dry Towers	1.0 %
Mechanical Draft Evaporative Towers	1.25%
Mechanical Draft Dry Towers	3.0 %

Of major interest as far as plant performance is concerned is the attainable condenser temperature using various cooling systems. The lower the condenser temperature (pressure), the better the plant heat rate which means more economical operation. Ritchings and Lotz (90) give the expected turbine exhaust pressure for a plant using the four major types of cooling towers and assuming different air temperatures, and plant load. This information is presented in Table 3.

Table 3. Comparative Cooling Tower Performance Data[b]

	35-Year	Summer	
	Average	Average	Maximum
Dry bulb temperature (°F)	50	70	95
Wet bulb temperature (°F)	40	55	65
Station load, percent	44	65	100
Turbine exhaust pressure (in. hg abs.)			
Induced-draft evaporative tower	1.3	1.6	2.7
Natural-draft evaporative tower	1.4	1.8	2.9
Induced draft dry tower	1.5	2.3	6.7
Natural draft dry tower	1.9	2.7	7.6

[b]From (90).

4.4 Combination of Cooling Methods

Situations may arise where a river or lake may have a heat load capacity which is adequate for most periods of the year but which may, at times, become inadequate because of excessive temperature, overload, or diminished water flow. In such cases it may prove practical to provide a combination of cooling methods by the addition of a cooling tower, cooling pond, or spray pond to whatever natural means are available.

In a combined once-through and cooling tower system, cooling water normally is pumped from the water source through the condenser and directly back into the source. During periods of high water temperature, cooling water from the condenser is pumped through a cooling tower before it returns to the stream. The amount of cooling by the tower will depend on the desired temperature decrease of the water leaving the condenser. The advantage of this combination is that the condenser water temperature is that of the river or lake while the water returned to the waterway is cooled to an acceptable temperature. Cooling towers for this type of application have two advantages which result in lower tower cost. First, the approach is larger and the range lower because only partial cooling is required. Second, the tower does not have to be constructed for heavy duty because it is expected to operate only two to three months each year. In some instances however, it is more economical to design the tower for full range and approach at partial flow, bypassing the rest of the water around the tower and mixing it with discharge from the tower before it is returned to the river. Kolflat (58) cites an installation where the optimum design condition is only 40% of total flow through the tower.

Another combined system in use is once-through cooling and a cooling pond. The cooling water is passed through a limited area cooling pond

before returning it to the river. The cooling pond is used to partially cool the discharge; not to act as a heat sink for totally recirculated water. A spray pond can also be used in the same manner.

Gausmann (44) notes that deep wells are a means of supplementing river flow and can be considered as part of a combined system. Wells may normally be developed at a plant site if there is a relatively porous strata of gravel adjacent to the river. The gravel deposits will be recharged each spring and will permit withdrawal of cool water during the dryer parts of the year. The Indianapolis Power and Light Co. has a capacity of 33,000 gpm in deep wells. Because of its low temperature (56°F) this well water is equivalent to nearly 100,000 gpm of river water. An advantage of using deep wells to supplement river flow is that all plants downstream benefit from the well water flow.

Smith and Bovier (91) note that construction of the Keystone Station of the Pennsylvania Electric Co. as a mine-mouth plant was made feasible by the combined use of natural draft cooling towers and a large artificial reservoir for cooling water makeup. The combination of a makeup storage reservoir with cooling towers makes it possible to locate large plants on streams with very small drainage areas. The total makeup requirement for the 1600 MWe Keystone Station for the four-month period July to October is about 7500 acre-feet. The reservoir stores 20,000 to 25,000 acre feet of water. It would be possible to operate the plant completely independently of natural stream flow during these months and still have a water reserve for abnormal conditions. An additional advantage of this combination compared with a cooling pond is that reservoir shape and configuration are not important since water storage only is desired rather than water surface for cooling. Also, the reservoir

may be located some distance from the plant. Considerable mobility in plant location is obtained by this combination.

4.5 Cost Comparison of Cooling Methods

Once-through cooling, under average conditions generally requires lower capital expenditures and lower operating costs than the use of a cooling tower or cooling pond. However, consideration of specific conditions must be given to each individual plant. For instance, siting to realize advantageous differences in fuel cost or transmission distance can make the production cost of a plant with a cooling tower or pond more economical than one with once-through cooling. This factor has motivated the building of mine-mouth plants with onshore cooling systems.

Economic studies of cooling systems normally take once-through cooling as the base system and compare the cost of cooling towers or ponds to the base cost. In calculating the cost of owning and operating a cooling tower, cooling pond, or spray pond, Gausmann (44) indicates that the following items should be included:

1. Annual investment cost. Including all annual charges (taxes, interest, insurance etc.) which will vary with the amount of the investment cost.
2. Auxiliary power charge. A fuel charge for the power used by the tower or pond system as well as a capacity charge based on the reduction in plant capability due to auxiliary power requirements.
3. Vacuum penalty. A fuel charge and a capacity charge for any difference in plant heat rate caused by a change in cooling water temperature.

4. Operation and maintenance costs. Includes increases in labor and in maintenance supplies caused by the installation.

Cooling tower costs are very sensitive to desired performance, particularly approach. This is illustrated in Fig. 26 which plots relative cost versus approach, range, and type of cooling tower.

Weir and Brittain (111) emphasize that an economic study of cooling systems should be integrated with the determination of optimum condenser size and configuration since the optimum size of either will depend on the size chosen for the other. Smith and Bovier (91) discuss the interrelation of cooling tower and condenser characteristics and the role this interrelation plays in selecting the most economical cooling system. This latter reference gives an excellent summary of the procedure used to select a site and cooling system for Pennsylvania Electric Company's Keystone Station. Among the studies conducted were:

1. A comprehensive review of coal resources and probable costs.
2. A plant site survey to locate mine-mouth plants within the service area which would be economically competitive with two previously acquired sites on the Allegheny River. The two river sites were capable of supporting once-through cooling.
3. Economic comparisons and feasibility studies of the following cooling systems: Once-through cooling, cooling towers combined with once-through cooling, a cooling pond, cooling towers only and cooling towers with a makeup reservoir.
4. Evaluation of optimum cooling tower and condenser combinations.

As a result of these investigations, a final economic comparison was made between a mine-mouth site using natural draft evaporative towers, with an artificial reservoir for makeup, and a once-through

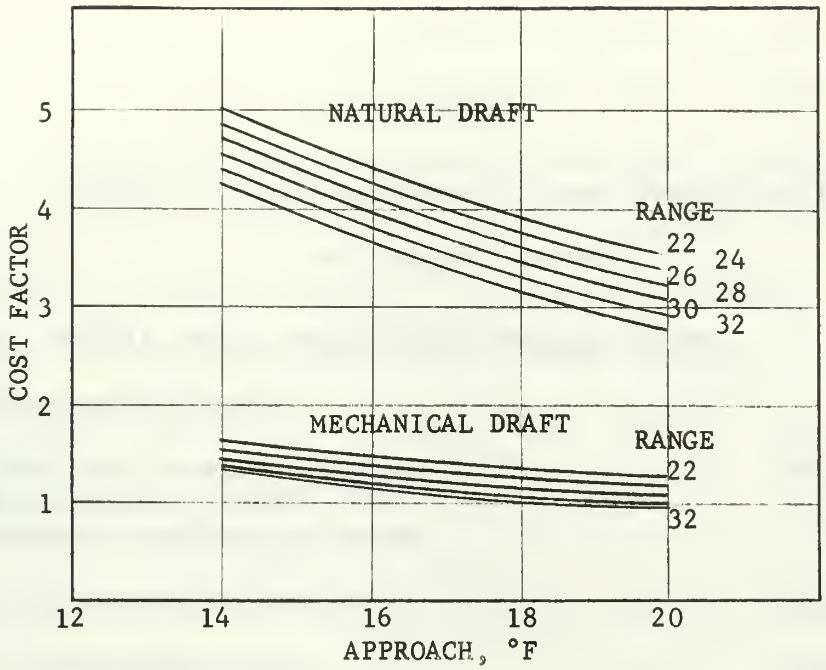


Figure 26. Relative cooling tower costs (56).

cooling system at an Allegheny River site. The comparison indicated that the cooling tower plant required a lower investment cost and also was more economical to operate when transmission and fuel costs were considered. A summary of this analysis is shown in Table 4.

In the case of these two sites, the cost of the cooling towers was more than offset by the cost of the intake and discharge tunnels, screens and pumphouse, and other equipment required with the once-through cooling system. In addition, the difference in excavation and related foundation costs between the two sites exceeded the cost of the storage reservoir. As a result of these factors, the cost of the cooling tower installation was about $1,600,000 less than the cost of a once-through plant on the Allegheny River. If the Allegheny River was as polluted and acidic as other rivers in the area, a stainless steel condenser would have had to be considered with the once-through system.

Table 4. Cost Comparison of Once-Through Cooling vs. Cooling Towers[c]

Additional initial costs, once-through cooling ($/kw)		
Cooling water circuit		
Intake and discharge tunnels	$2.10	
Screen house, screens, etc.	1.70	
Condenser, piping and valves	.94	
Building excavation and related costs	1.66	
Total additional costs	$6.40	
Additional initial costs, cooling tower plant ($/kw)		
Cooling towers	$4.20	
Storage reservoir and related costs	1.20	
Total additional costs	$5.40	
Initial cost savings with cooling tower plant ($/kw)		$ 1.00
Operating penalties with cooling tower plant ($/kw)		-1.62
Transmission and fuel cost credits with cooling tower plant ($/kw)		18.54
Net economic advantage with cooling tower plant ($/kw)		$17.92

[c]From (91).

The cost differential would then have been increased to about $4,000,000. The operating penalties associated with the cooling tower site for higher condenser temperature, increased pumping power, and losses in capability amount to $1.62 per kw which exceeds the savings over once-through cooling in initial investment. However a 3¢ per million Btu fuel cost advantage and a twenty-mile reduction in transmission distance overwhelmingly compensate and result in a total evaluated savings of $17.92 per kw in favor of the cooling tower site.

This study illustrates the sensitivity of plant site selection, and indirectly cooling system selection, to fuel cost and transmission distance. A quantitative illustration of this sensitivity is available from a study made by the Indianapolis Power and Light Company and presented by Gausmann (44). The study considered a mechanical draft cooling tower for a 100 MWe unit, where the tower would only be operated about 10% of the time - during periods of low river flow. Therefore, low construction costs were a prime objective in tower design. The annual cost of owning and operating the tower was found to be equivalent to an increase in annual cost caused by any of the following variables:

1. Increase in transmission line length of 14 miles.
2. Increase in coal cost of 33¢ per ton (1.4¢ per million Btu). Typical coal costs are 20¢ to 40¢ per million Btu.
3. Increase in plant cost of $6.95 per kw (typical plant costs are $100 to $150 per kw).

As an example, if the plant was moved more than 14 miles farther away from the load center to enable once-through cooling to be used, it would be more economical to use the cooling towers. The absolute cost of increasing transmission line distance can be estimated from the

figures below, given by Ritchings and Lotz (90):

Circuit	Estimated Cost per Mile
138 kv double circuit	\$25,000
138 kv single circuit	\$15,000
220 kv double circuit	\$60,000
230 kv single circuit	\$40,000

Circuit	Distance	Line Loss
138 kv	50 miles	3.35%
230 kv	100 miles	1.80%
230 kv	150 miles	2.60%
230 kv	200 miles	3.60%
230 kv	250 miles	4.40%

Normally, for large plants, one or more double circuit lines would be installed and transmission voltage would be 138 kv up to 75 miles. At distances over 75 miles 230 kv, or more recently 500 kv or 750 kv would be used. The cost of 500 kv transmission line ranges from \$85,000 to \$100,000 per mile; and 750 kv, \$125,000 to \$160,000 per mile. The costs of transmission line that have been cited include land, erection, and equipment costs.

A different plant economic study, presented by Steur (95), indicates that a change in fuel costs of only 0.8¢ per 10^6 Btu (19¢ per ton of coal) was sufficient to offset the higher capital cost and heat rates if the plant used cooling towers versus once-through cooling.

For nuclear plants, fuel costs are essentially unaffected by plant location. Therefore water requirements and restrictions, and transmission distance, are the major variables in the economic selection of

the plant site and cooling system. A recent report by Converse (15) evaluates the cost of cooling the Vermont Yankee Nuclear Power Corporation's 540 MWe nuclear plant at Vernon, Vermont. Five different cooling systems are compared and their effect on production costs and costs to the consumer are estimated. The results of this report are summarized in Table 5. Thermal pollution considerations motivated Vermont Yankee to select a combined cooling tower and once-through system at a differential annual cost increase of about $900,000 per year over once-through cooling alone.

Other economic studies have indicated cooling ponds, once-through cooling, or mechanical draft cooling towers as the least costly method of cooling. The results of the most detailed and comprehensive of these studies is presented in Table 6. The study was conducted by Ritchings and Lotz (90) for a hypothetical 200 MWe coal-fired plant located in the Southwest United States. Because water supply resources are limited in this region, once-through cooling was not considered. Four different cooling tower systems were considered: mechanical induced draft evaporative, natural draft evaporative, natural draft dry, and induced draft dry. The mechanical, induced draft evaporative tower is found to be the most economical for the conditions considered; and the induced draft dry tower the most costly. The article describing this study is particularly informative because of the detailed description presented of the design and operating characteristics of the various systems and the explicit breakdown of costs. In Braswell's study (10) of the cooling pond built for the Delta Station of the Mississippi Power and Light Company he indicates a fixed plus fuel cost differential of $50,000 per year in favor of the pond over cooling towers. Sixty

Table 5. Economic Effect of Plant Cooling Systems Alternatives[d]

Cooling System	Production Cost Mills/kwhr	Percent Increase in Production Cost	Percent Increase in Cost to Consumer	Annual Cost Increase, $/yr
Once-through	4.02	base	base	base
Once-through and mechanical draft, evaporative cooling tower combination	4.19	4.2	.84	680,000
Mechanical draft evaporative cooling towers	4.22	5.0	1.0	800,000
Mechanical draft dry cooling towers	4.59	14.2	2.82	2,280,000

[d]From (15).

Table 6. Comparison of Costs of Cooling Tower Systems for a 200 MWe Coal-Fired Powerplant[e]

		Induced Draft Evaporative Towers	Natural Draft Evaporative Towers	Natural Draft Dry Towers	Induced Draft Dry Towers
Investment					
Total Plant Investment	($)	28,715,000	29,580,000	31,905,000	32,305,000
Differential	($)	base	863,000	3,190,000	3,590,000
Annual Costs (Excluding Capability Loss)					
Fixed Charges at 13.5%	($)	3,877,000	3,953,000	4,307,000	4,361,000
Auxiliary Power Cost	($)	133,000	121,000	130,000	176,000
Fuel Cost	($)	2,072,000	2,076,000	2,102,000	2,084,000
Maintenance	($)	211,000	195,000	214,000	216,000
Water Treatment Chemicals	($)	55,000	22,000	16,000	16,000
Total	($)	6,348,000	6,407,000	6,769,000	6,853,000
Differential	($)	base	59,000	421,000	505,000
Capability Loss					
Auxiliary Power at $13.5/kw	($)	33,000	20,000	30,000	74,000
Summer Capability at $13.5/kw	($)	72,000	49,000	418,000	356,000
Total	($)	105,000	69,000	448,000	430,000
Annual Costs Plus Capability Loss					
Total	($)	6,453,000	6,476,000	7,217,000	7,283,000
Total Annual Differential Costs	($)	base	23,000	764,000	830,000

[e] From (90).

percent of this differential is due to the higher plant thermal efficiency available with the pond. Once-through cooling was not considered to be economically competitive with towers or a pond for the station.

As previously stated however, if a water supply is available, once-through cooling is generally the least costly system.

Approximate values of the additional capital investment required for various types of cooling tower installations, over that required for a once-through system are given by Kolflat (58) as follows: \$6/kw for induced draft evaporative towers, \$11/kw for natural draft evaporative towers, \$25/kw for natural draft dry towers, and \$27/kw for induced draft dry towers. These figures do not include annual operating and maintenance expenses.

However, the Federal Water Pollution Control Administration's "Industrial Waste Guide on Thermal Pollution" (40) notes that approximate values such as these can be grossly misleading; and it is possible that the optimum cooling tower installations for two plants with identical rated outputs could differ in cost by a factor of two. This is mainly because land and fuel costs vary widely with location. The guide indicates in summary that evaporative cooling systems will generally increase the capital cost of a power plant by about 5%, and that power production costs are also increased by about 5%. However, Converse (15) notes that production cost is only about one-fifth of consumer cost so that the cost of electricity to the consumer, because of evaporative cooling towers, would only increase about 1%.

It is apparent that the economic penalties normally associated with onshore cooling systems are not as serious as often has been the belief. Onshore systems may be particularly attractive whenever good river, lake,

or ocean sites are unavailable or when the plant site can be located to take advantage of reduced fuel and transmission costs. These conditions are exploited when a fossil fuel plant is built at a mine location. For nuclear and fossil fuel plants, onshore cooling systems should be considered to avoid poor foundation conditions, long transmission distances, and violation of legislated water temperature restrictions.

V. CONTROL OF THERMAL POLLUTION

5.1 Methods to Minimize Effects of Rejected Waste Heat

5.1.1 Prediction of Effects

In order to predict and evaluate the effects of a waste heat load in any specific situation, it is necessary to have a rational method of forecasting heat dissipation and the corresponding water temperature profile expected along the course of the receiving stream.

Before deciding on the cooling water discharge arrangement for any particular site which does not employ a closed cycle cooling system such as cooling towers, studies are made to predict the water temperature distribution in the waterway receiving the discharged coolant. These studies provide an indication of the likelihood of recirculation and of the probability of significant biological disturbances. Design measures can then be taken to prevent predicted undesirable effects such as a thermal barrier to spawning fish, recirculation, or an excessive water temperature increase.

Brady and Geyer (9) indicate that preliminary predictive studies normally employ a combination of the following techniques:

1. Analyses of data from existing plants.
2. Mathematical analyses.
3. Hydraulic models.
4. Simulation by computer.

The first technique is applicable only if field data is available from existing plants in similar situations and locations. In the case of mathematical analyses, applicability depends on the simplifying assumptions that can be made concerning the geometry of the particular site and its flow behavior. Hydraulic models are often capable of simulating

regularly fluctuating flow conditions (such as tidal oscillations), but cannot properly simulate all of the important zones comprising a discharge system (e.g., zones of plume entrainment, stratified flow, general turbulance etc.)

There are several important advantages in using a computer to predict the response of receiving waters to thermal discharges:

1. The large capacity of computers can cope with the continually varying and complex interactions between the many variables present in a discharge problem.
2. Diurnal variations of meteorological conditions, especially solar radiation, windspeed, and relative humidity, can be realistically simulated.
3. Many years of real time behavior can be simulated in a relatively short computing time.

Since 1953, the AEC has been studying a variety of effects, including thermal effects, on the Columbia River in connection with the operation of the nuclear reactors at the Hanford Works in Washington (103). One result of these studies has been the development of a computer model that uses historical data and basic mass transfer relationships to predict the downstream temperature effects at Hanford of selective withdrawals of cool water from Lake Roosevelt. The computer code, called Colheat, is used regularly for predicting Columbia River temperatures above and below the Hanford plant. Colheat can simulate and predict river water temperatures over an extensive regional area for a wide range of actual and hypothetical conditions, including the addition of heat from powerplants of any number, efficiency, and location. Brady and Geyer (9) note that there are other computer codes that also model

the response of receiving waters to thermal discharges but that none of these existing codes approach the complexity envisioned for the future. The main new features which they feel would be desirable to incorporate in future models would be:

1. Variable salinity, both horizontal and vertical.
2. Variable diffusivity, both horizontal and vertical.
3. Historically factual and/or simulated extreme diurnal and seasonal fluctuations in flow and meteorological conditions.
4. Simulated biological behavior, including food chain and reproductive cycles, based on detailed field and laboratory observations of biological responses by significant organisms to temperature and other environmental factors.

The most difficult problem encountered in producing a successful mathematical or computer model for a particular type of water body is the development of the temperature equation.

It is necessary to consider heat transfer mechanisms in water and between water and the atmosphere in order to describe temperature regimes mathematically. There are two heat transport mechanisms which occur in water - advection and dispersion or turbulent mixing. Advection is the transport of heat by the motion of a mass of water and is accomplished by ordinary streamflow, utilization of a discharge stream's kinetic energy, or water movement due to density gradients. Mathematical terms for advection express the rate of heat energy transfer in terms of the water mass temperature and velocity along longitudinal, lateral, or vertical axes. Turbulent mixing or dispersion causes heat interchange through eddy diffusion or molecular diffusion. Eddy

diffusion occurs under turbulent flow, which depends on fluid velocity and channel characteristics. Mixing results from the action of small fluid masses known as eddies, which are random in size and orientation. Molecular diffusion results from random motion of molecules and is not as significant as turbulent mixing. The heat transfer or exchange which takes place between the water surface and the atmosphere depends on the processes of evaporation, convection, and radiation. The various mechanisms involved in this exchange were discussed in the previous section of this paper under Cooling Ponds.

In the analysis of cooling water discharges, a continuity relationship in the form of the conservation of heat equation is applied to the temporal and spatial distribution of heat in the water. The equation for the conservation of heat can be presented in differential form. Using a three dimensional rectangular coordinate system with the x_1 and x_2 axes in the plane of the water surface, and the x_3 axis extending perpendicularly downward from the water surface, Edinger and Geyer (26) give the general differential equation for a small elemental volume of fluid as:

$$\rho c_p \left(\frac{\partial T}{\partial t} + V_1 \frac{\partial T}{\partial x_1} + V_2 \frac{\partial T}{\partial x_2} + V_3 \frac{\partial T}{\partial x_3} \right)$$

$$- \frac{\partial}{\partial x_1}\left(D_1 \frac{\partial T}{\partial x_1} \right) - \frac{\partial}{\partial x_2}\left(D_2 \frac{\partial T}{\partial x_2} \right) - \frac{\partial}{\partial x_3}\left(D_3 \frac{\partial T}{\partial x_3} \right) = S \frac{\text{Btu}}{\text{ft}^3 - \text{day}}$$

where: ρ = density of water in lbm/ft^3

c_p = specific heat of water in Btu/lbm °F

T = temperature, °F, within the elemental volume

t = time in days

V_1, V_2, V_3 = fluid velocities in ft/day in the x_1, x_2, and x_3 directions respectively

$\frac{\partial}{\partial x_1}, \frac{\partial}{\partial x_2}, \frac{\partial}{\partial x_3}$ = derivatives in the x_1, x_2, and x_3 directions respectively

D_1, D_2, D_3 = coefficients of turbulent mixing in the x_1, x_2, and x_3 directions respectively in ft^2/day

S = the "heat source" term in Btu/ft^3 - day

The first term in the above equation is the time rate of change at which heat is gained or lost in the elemental volume. The terms involving the velocities V_1, V_2, and V_3 are advection terms and give the rate at which heat is added or removed due to the fluid flow in the direction of the temperature gradients through the elemental volume. The rate at which heat is added or removed by turbulent transport is given by the set of terms involving the mixing coefficients D_1, D_2, and D_3. The "heat source" term is normally replaced by a term expressing the surface heat transfer rate. Use of this equation in its complete form is virtually impossible. It can be handled, however, when the number of factors to be accounted for are reduced to the dominate transport mechanisms operating in a particular case. Edinger and Geyer discuss several practical situations involving retention of only the significant terms in the general equation such as a completely mixed stream.

A primary objective of predictive temperature studies is to define the area or zone of significant temperature change - the mixing zone (discussed in more detail under section 5.4, Water Temperature Restrictions). Legislated water quality criteria may specify an allowable mixing zone where some of the water temperature restrictions may be waived. If predictive studies can show that mixing of the cooling water and river water is sufficient to reduce the bulk water temperature to an acceptable value before it leaves the defined mixing zone, a costly onshore cooling system may be avoided. The report by Edinger and

Geyer presents a development of relations that can be used to predict mixing zone temperature using cooling water flow rate, cooling water temperature out of the condenser, total river flow, unheated river water temperature, and the amount of mixing taking place.

A new technique which may find wide use in predictive studies is airborne infrared mapping. Some specific applications to the thermal pollution problem as listed by Van Lopik et al. (104) are:

1. Determination of thermal circulation and diffusion patterns produced in waterways by cooling water discharges from powerplants.
2. Assisting in the development of a thermal pollution index based on areal thermal data and water body dynamics.
3. Detection of thermal pollution and measurement of river temperature and temperature decline downstream from a heated discharge.
4. Establishment of natural seasonal and diurnal ranges of water-surface temperatures before construction of plants that will discharge heated water.

5.1.2 Dispersion and Dilution

As noted previously, the waste heat contained in cooling water discharges is dissipated by various combinations of mass advection, mixing (dispersion and dilution), and surface cooling (heat transfer to atmosphere). However, because observed rates of heat transfer due to surface cooling are relatively low, and because pure advection provides no lowering of temperature, in order to avoid large mixing zones (zones of high temperature near thermal discharges) dispersion and dilution

must be depended on. Under these conditions, the bulk of the waste heat is ultimately lost from the water by surface cooling at relatively large distances from the discharge location (and at a greatly reduced temperature difference).

One method available for holding down the heating effect of the discharged cooling water is to use a larger volume of cooling water so that it is heated less. Condenser cooling water temperature rise is inversely proportional to its flow rate. Higher flow rates mean lower temperatures, but also higher pumping costs. A cooling water temperature rise of 10°F is about the minimum that is acceptable economically.

The basic mechanism of heat dispersion and dilution is turbulent mixing. Jensen and Brady (54), in their report concerning available techniques of achieving the desired mixing and its biological implications, consider two separate conditions - natural turbulence and induced turbulence. Natural turbulence results from bottom and wind-induced friction and from the dissipation of momentum due to curved alignments in rivers and tidal waters. In relatively straight rivers, the highest velocities generally occur in the central region of the stream near the surface. The zone of highest velocity gradient (which constitutes a major source of turbulence) is also located near mid-stream below the high velocity zone. However, fish migrations (both upstream and downstream) usually take place fairly close to the shoreline, thereby indicating a biological preference for the shoreline as a feeding zone, and a simultaneous tendency to avoid the mid-stream zone of high velocity and turbulence. Therefore, significant advantages might be gained by locating cooling water discharge structures in mid-stream on relatively straight rivers (or estuaries), in order to benefit

from the improved mixing due to natural turbulence and simultaneously reduce the likelihood of biological disturbances. The location of power-plants near bends in curved rivers, so as to take advantage of increased turbulence due to such natural configurations is another alternative. In particular, cooling water discharges located near the downstream ends of river bends (on the outer bank) exhibit much higher rates of heat dissipation due to natural turbulent mixing than for similar discharges on straight sections of a river. The increased mixing appears to be due to components of flow vortices (with axes parallel to the flow) which form in the downstream portions of the bends due to the tendency for conservation of angular momentum in the upstream vertical "rolling" motion (induced by the action of bottom friction).

Richards (88) notes that in circumstances where natural turbulence is not sufficient to provide adequate dispersion and dilution by mixing, the rapid horizontal discharge of cooling water (employing the principle of the momentum jet) can provide additional turbulence to reduce the zone of significantly warmed water. The cooling water is discharged at the surface with a horizontal velocity of 2 to 8 fps. The momentum of the jet, if properly directed, will carry the heated water several thousand feet into the waterway, almost as effectively as a closed conduit. The warmed jet will be quickly moved out into a river cross section or into a tide race where rapid mixing can take place. Where a relatively low velocity jet of this type can be utilized without disturbing small boats, barge tows, or fish migrations, it is more economical than extending a conduit far out into the waterway. Jensen and Brady (54) state that since experience suggests fish tend to avoid zones of excessive velocity gradients, and since the turbulence is likely to

be more intense in the immediate vicinity of the jet discharge orifice (where the temperature of the cooling water is also highest), momentum jet discharges may achieve dual benefits in both heat dissipation and biological protection.

The reduction of temperatures in the mixing zone can also be achieved by the installation of auxiliary pumping units which bypass the condenser and merely dilute (and provide increased turbulent mixing in) the cooling water flow with additional water from the intake side. A typical installation using this dilution technique was proposed for the Oyster Creek Nuclear Plant of the Jersey Central Power and Light Company. Cooling water flow to the condensers of this 640 MWe unit is 460,000 gpm; an additional 780,000 gpm was to be pumped from the intake directly to the discharge canal and mixed with the heated effluent prior to discharge to Barnegat Bay (88). Additional pumping power is required in this scheme but since the dilution can take place in large outdoor mixing areas, lower pump heads can be used; and the required additional pump power is less than with increased condenser flow for the same ultimate discharge temperature.

An installation which takes advantage of both natural and induced turbulance for mixing is the Hanford Nuclear Generating Station of the Washington Public Power Supply System. The cooling water (564,000 gpm) from this 860 MWe plant is carried at 13 fps in a conduit (11 ft. in diameter and 1000 ft. long) to mid-channel of the Columbia River where it is discharged through four vaned outlets (88).

To reduce the size of the mixing zone in Wheeler Reservoir below TVA's Browns Ferry Plant, cooling water is discharged through a multiport, submarine diffuser system (11). The system consists of three

partially perforated pipes connected to the discharge conduits from each of three turbine condensers. The corrugated, galvanized steel pipes are laid in three parallel lines across the bottom of the 1800-foot-wide channel which is about 30 feet deep. The pipes (17 ft., 19 ft., and $20\frac{1}{2}$ ft. in diameter) are of three different lengths and the last 600 feet of each pipe is perforated on the downstream side with more than 7000 two-inch-diameter holes which distribute the cooling water into the river for thermal mixing. The main channel where mixing takes place occupies about 25 percent of the flow. The system provides a zone outside the main channel which is not appreciably affected by the plant i.e., there is not a "thermal block" in the reservoir, so that migration of aquatic life can occur without interference.

The objectives of the techniques discussed thus far are to maximize turbulence and mixing, and disperse the rejected heat through as large a volume of the receiving water as is permissable. A method with the opposite objective is also used by the TVA. A discharge canal is used which floats the warm cooling water on the surface of the receiving waterway. This arrangement maximizes dissipation of heat to the atmosphere and minimizes the water volume affected by the effluent; mixing is not desired. By forming a warm water wedge over the cool receiving water, rapid heat loss to the atmosphere is promoted by increasing heat loss due to evaporation, convection, and radiation. The warm water wedge or layer acts in much the same manner as a cooling pond. However, this technique results in sharp temperature gradients near the surface and adverse biological effects may result if surface feeding aquatic species are subjected to these gradients.

If the discharge arrangement of a cooling system is not

specifically designed for maximum dispersion or dilution, or for a "floating layer" discharge, a form of the latter will result naturally because of differences in water density between the heated cooling water and the unheated water of the receiving waterway. Engle (33) reports on a study conducted at the Martins Creek Station of the Pennsylvania Power and Light Company which established depth-temperature profiles on the Delaware River to 3000 feet downstream from the cooling water discharge. The discharge system was not designed to specifically mix the cooling water with the river water or float it on the river surface. Conclusions reached in this study indicated that the hot water rose to the surface of the river and did not affect the river water more than $2\frac{1}{2}$ feet below the surface at a point 300 feet downstream of the discharge.

5.1.3 Siting

The choice of location for a powerplant is a function of many complex factors including the location and type of demand to be met, the type of facility (nuclear, fossil fuel, hydro) to be built and its capacity, fuel availability, and various political, conservation and esthetic constraints. The increase in public concern about thermal pollution has added a new factor to be considered in plant siting, the effect on the aquatic environment.

A joint effort by aquatic biologists and engineers in locating a plant site can be effective in reducing the effect of a heated discharge. A biological reconnaissance can provide preliminary data on the ecology and assist in avoiding obvious problem areas such as habitats for cold water fishes and migratory pathways for anadromous fishes. The engineers must examine physical data and other criteria including costs.

When the biologist and engineers agree on a site which can assimilate a heated discharge, a further determination must be made of the maximum temperature that can be tolerated. This may require model studies and detailed ecological studies covering a period of several years.

The report "When Do Stream Temperatures Become a Problem" by Moyer and Raney (73) describes in detail a typical siting study for the Peach Bottom Atomic Power Station of the Philadelphia Electric Company. In this report, the authors note that the most important information required for the engineer to design for minimal thermal effects is:

1. Stream flow data, natural river water temperature and wet bulb temperature ranges at or near the site.
2. Agreement with regulatory authorities as to the extent of the mixing zone.
3. Agreement on maximum temperature increases permissible in the fishways outside the mixing zone.
4. Agreement as to where and when the temperatures will be monitored.

Another comprehensive report describing the techniques employed in conducting a powerplant site survey is "Field Sites and Survey Methods" by Geyer et al. (45).

The problem of plant siting has thus far shown only limited adaptability to a computer solution because of the many intangibles involved. A recent report by Marks (65) describes a computer program for selecting the optimal location of a powerplant subject to some economic and environmental constraints.

The use of aquatic biologists and the conduct of ecological reconaissance studies at proposed plant sites has become the rule rather

than the exception in plant siting. This trend is not only a result of the increasing number of legislated water temperature restrictions but also because of the growing public attitude that it should be the responsibility of those who wish to alter the environment to take action to minimize the effects of such alterations. In the recent report by The Energy Policy Staff of the President's Office of Science and Technology (32), each applicant for a powerplant construction permit was urged to follow the following guidelines:

1. Cooperate with the Fish and Wildlife Service, the Federal Water Pollution Control Administration, the State Fish and Game Boards, and other interested agencies in developing plans for ecological studies and surveys.
2. Construct, operate, and maintain such fish protective structures as are needed to prevent significant damage to fishery resources.
3. Make such modifications in project structures and operations as may be found necessary as a result of ecological studies and surveys.

One solution to minimizing thermal effects by plant siting is to build smaller capacity plants in greater number so that the plants could be spread along a water body to lessen the heat impact at a particular point. Gausmann (44) indicates that in general the distance between plants on the same river need not exceed 10 to 15 miles. Kolflat (56) presents an analysis showing which rivers in the U. S. are capable of supporting powerplants of 2000 MWe placed every 10 miles along the waterway with various upper water temperature limits. He suggests that as power demand increases, water-use zoning may be desirable. This

would allow temperature increases beyond legislated limits for specified reaches of a river so that powerplant once-through cooling could be accomodated.

Another siting technique which may reduce thermal pollution is to locate a steam powerplant downstream of a hydroelectric plant so that its operation may be coordinated with the hydro plant to obtain the best possible use of the water. Locating a plant at a bend in the river rather than on a straight reach can offer better mixing and quicker dispersion of waste heat due to greater turbulence, as discussed in a previous section of this paper (Dispersion and Dilution). Or a plant might be located on a backwater of a river where aquatic life is least important, so that the heated discharge is harmless by the time the tributary enters the main stream.

The siting problems discussed here are related mainly to plants which use once-through cooling wholly or in combination with some other system. If an onshore, closed cooling system is used, there is no problem in siting from the aspect of thermal pollution to the waterway.

5.1.4 Operational Control of Powerplants

Methods of reducing thermal effects in this category include reducing plant load, restricting the rate of change of plant load, and shutdown of the plant during selected time periods.

Churchill and Wojtalik (13) report that in 1959, TVA voluntarily decided that for their Paradise Plant on the Green River, mixed river water temperature should not exceed 95°F. It was decided that plant load would be cut back whenever necessary to prevent the temperature from exceeding 95°F. Four temperature sensors were installed in a

cross section of the river downstream from the plant and temperatures telemetered to the control room of the powerplant. This proved effective and prevented excessive temperatures during the summer months during periods of low flow. More recently, Niagara Mohawk indicated a willingness to reduce plant load by as much as 20% when necessary, to prevent exceeding maximum water temperature limits at their Easton Plant in upstate New York (110). It was determined that this was a more economical solution than having to build cooling towers.

A recommendation similar in concept is to shut down a powerplant for normal maintenance during the summer months when the climate and hydrological factors combine to make waste heat rejection most hazardous. This proposal, however, is not practical from the point of view of meeting electrical load requirements. Peak load operation occurs during the summer months due to air conditioning and refrigeration power requirements.

Another operational technique possible is to coordinate peak load operation with water releases from upstream hydroelectric plants to prevent excessive temperature increases caused by inadequate flow.

To prevent aquatic life from a sudden sharp change in temperature, a number of states have adopted rate-of-change temperature criteria. The restriction imposed on powerplant operation by these criteria means that where they are applicable, powerplants may have to operate at a constant or slowly changing load i.e., base load plants. Peaking plants - plants responding to the wide daily variation in load - would have to be cooled by an onshore system or a combination of systems (or be powered by non-steam prime movers not requiring much cooling water).

5.2 Methods to Reduce the Amount of Waste Heat

For steam powerplants, reducing the amount of waste heat means improving current Rankine cycle technology. Energy conversion is more efficient today than 25 to 30 years ago. The Federal Power Commission (FPC) reports that the average plant heat rate is now less than 10,000 Btu/kw (efficiency of 34%) as compared to 16,500 Btu/kw (21% efficiency) in 1934 (38). The FPC also predicts that an average heat rate of 8500 Btu/kw is likely by 1980. While this would reduce the current average thermal discharge by almost 20%, it still means an average plant thermal efficiency of only 40%. Even with the estimated increases in plant efficiency, the cumulative heat discharge to cooling water will double due to increased power demands.

The development of new energy conversion principles offers the greatest possibility of a significant increase in energy conversion efficiency and reduction in waste heat discharge.

3.2.1 Improvement of Rankine Cycle Technology

From the comparative thermodynamic analysis presented previously, it is apparent that modern powerplants currently employ numerous techniques to obtain the maximum efficiency from the power cycle. The realizable efficiency from these plants is limited, however, by the comparatively low operating temperatures. Even though furnace gases reach 3300°F in fossil fuel plants, metallurgical considerations normally limit steam temperatures to something less than 1300°F (3). In water-cooled nuclear reactors, the necessity of keeping zircaloy fuel cladding below a temperature of about 660°F to prevent excessive corrosion and embrittlement further limits maximum steam temperature (102). An area that does hold promise for increasing the maximum steam temperature,

and thus plant thermal efficiency, is high temperature turbine blade cooling.

Development of non-water cooled reactors for commercial applications offers the opportunity to improve heat rejection rates from the increasing number of nuclear powerplants. High temperature gas cooled reactors (HTGR), molten salt breeder reactors (MSBR), and liquid metal fast breeder reactors (LMFBR) all have the capability to produce steam conditions, and thus plant efficiencies, comparable to modern fossil fuel plants. Gamble and Fowler (42) report that a current HTGR design of 330 MWe for the Public Service Co. of Colorado will have steam conditions of 2400 psia, 1000°F, with reheat to 1000°F. The thermal efficiency of this plant will be greater than 39% - equal to most modern fossil fuel plants and therefore having a comparable heat rejection rate.

5.2.2 New Methods of Generating Electricity

5.2.2.1 Gas Turbines

Although not a new method, gas turbines offer a means of power production without cooling water. Air is taken from the atmosphere, compressed, mixed with a fuel, and burned. The high-temperature, high-pressure combustion gases then expand through a power turbine and exit to the atmosphere. Current gas turbine efficiencies of less than 25% make them uncompetitive for power production on a large scale; however they are used for standby and peak load operation.

A recent development in the gas turbine field which does show promise is the coal gasifier - gas turbine. The process consists of onsite gasification of coal under pressure (30 atmospheres) in an entrained airblown gasifier, removal of hydrogen sulfide from the gas produced, and then combustion in a cycle in which a major portion of the

generator driving energy is provided by gas turbines (30). It is estimated that a gasifier - gas turbine plant would operate with an efficiency of about 41% with very little heat rejection to cooling water as compared to that from a steam plant.

5.2.2.2 Thermoelectric Generation

Thermoelectric generation, makes use of the principle that a potential difference will be produced when heat is applied to one of the joined ends of two dissimilar conductors. The thermocouple is an example. Advances in solid state physics have made possible the development of semi-conductors which permit improved efficiencies over those achieved previously with metallic type junctions.

Bismuth, lead, and germanium tellurides with certain additives, such as selenium, as well as many other compounds have been used. In order to accommodate wide temperature ranges, various materials can be used so that each may operate at a temperature where its efficiency is best. To obtain usable amounts of power, the coupling together of a large number of junctions is required. Low-voltage direct current power is produced.

Thermoelectric generators have been built and operated successfully for significant lengths of time. Generators, fueled by isotopes, are being used for military, space, and oceanographic applications to provide remote unattended power sources. Capacities ranging from a few watts to five kilowatts have been achieved. Present problems include longevity of thermoelectric elements and low plant efficiencies.

Present estimates forecast a rather small, 200 kilowatt, power capability for this method by 1980 (38). Theory also

indicates that all thermoelectric materials appear limited to about a 30% materials efficiency. When the Carnot efficiency and the heat generator efficiency are superimposed on the materials efficiency, it seems that the overall efficiency for thermoelectric generation may be limited to 10%. Therefore, even if larger capabilities should develop, it is generally conceded that thermoelectric generation will not be economic except for special applications. Capital costs are expected to be in the \$200 to \$500 per kilowatt range by 1980 (38). Thermoelectric generators normally use the atmosphere as a heat sink and thermal pollution of cooling water is not a problem.

5.2.2.3 <u>Thermionic Generation</u>

The basic principle of operation of thermionic devices is based on the phenomenon of electron emission from metals at high temperatures. The conventional vacuum tube is an application of thermionic emission.

A thermionic converter contains an electron emitter, called the cathode, which is heated causing electrons to boil off. These electrons have enough energy to move through an intervening space to a cooled electron collector, known as the anode. The potential thus created will cause a current to flow in an external load. The output is usually low-voltage direct current.

Thermionic converters, combining satisfactory operating and economic characteristics, are still in the development stage. The major problems are emitter materials and fabrication. The requirement of a high temperature (3000°F) suggests the use of a nuclear reactor as the best heat source; and the use of in-core elements as promising the highest performance and most compact units.

Hydrocarbon-fueled thermionic converters are also feasible; however, considerations of heat transfer and combustor efficiency limit their overall efficiency to perhaps less than half that of the in-core converter.

The Federal Power Commission predicts that by 1980, due to improvements in technology especially in fabrication of in-core thermionic fuel elements, 100 megawatt thermionic reactor units may be "topping" the steam cycle in a nuclear plant (38). The efficiency of thermionic converters may ultimately be as high as 30 to 40 percent. By using them to top a conventional steam cycle it would be possible to increase plant efficiency by as much as 15% and thus reduce the amount of waste heat rejection per kwhr of electric power produced.

5.2.2.4 Magnetohydrodynamic (MHD) Generation

Generation of power using magnetohydrodynamics is based on the same principle governing power generation in a conventional generator. Instead of a solid conductor rotating in a magnetic field, a jet of high-temperature high-velocity ionized gas is forced through the magnetic field. By placing electrodes in this hot gas stream, direct current electric power at relatively high voltages e.g., 2000 volts or more, can be obtained.

The generation of electric power by MHD principles has been demonstrated in a number of laboratories. All tests have shown, however, that the required high temperatures create a serious materials problem, both for the electrodes and the MHD duct lining.

Because of the high-temperature exhaust of the MHD device, and for technical and economic reasons, the use of the combination MHD-steam cycle appears more practical for central station

generation than using the MHD generator alone. The high temperature exhaust of the MHD would be used to generate steam for a conventional steam powerplant in addition to MHD produced power.

Although high temperature, gas-cooled, reactor technology has developed to a point where a closed cycle nuclear approach for MHD is becoming practical, the open-cycle fossil fuel approach to MHD is currently more attractive since a high-temperature fossil fuel technology exists, and there is a greater latitude in the selection of high-temperature resistant materials. The American Electric Power Corporation and Avco Corporation currently plan to build and operate an experimental 30 MWe fossil fuel steam/MHD plant (30).

An MHD generator is primarily suited to be a bulk power generator and, when combined with a conventional steam plant, will be best suited for plant sizes ranging from 300 megawatts to over 1,000 megawatts. The Federal Power Commission predicts that, if the basic problems are solved, the MHD plant, with the open-cycle fossil fuel fired unit and possibly the closed-cycle nuclear unit, could be established by 1980 as a prime bulk power generator in unit sizes up to 1,000 megawatts (38). The FPC estimates efficiencies of the open cycle to range from 50% to 55%, and studies of a closed-cycle unit show efficiencies over 60%. By 1980, it is predicted that it should be possible to build an MHD plant for $120 to $150 per kilowatt. The predicted 10% to 20% gain in efficiency with MHD powerplants as compared to current steam powerplants, would result in a sizable reduction in thermal pollution.

5.2.2.5 Fuel Cells

Fuel cells, are electrochemical devices in which

chemical energy of conventional fuels is converted directly into low voltage direct current. Fuel cells have the basic elements of a battery, positive and negative poles, and an electrolyte. However, unlike batteries they do not store the energy to be converted in the cell. In any type of fuel cell it is necessary to combine the fuel, such as hydrogen, with the oxidant which may be either commercial oxygen or air. The driving force that keeps the fuel cell operating is the free energy of the reaction.

The chemistry of the hydrogen-oxygen cell is fairly simple. At the oxygen electrode, hydroxyl ions are formed removing electrons and leaving the electrode positive. At the hydrogen electrodes, hydroxyl ions combine with hydrogen to form water giving off electrons in the process. Consequently, the hydrogen electrode becomes negatively charged with respect to the oxygen electrode, and a current can be made to flow through an external circuit.

While fuel cells operating on pure hydrogen and oxygen are currently being used in a few limited military and space applications, they are neither commercially available in large sizes nor economic in operation at the present time. A major thermodynamic advantage of fuel cells which produce electricity through oxidation of hydrogen or hydrocarbon fuels is that they are not limited to Carnot efficiencies.

The earliest commercial applications appear to be as mobile power sources. Likely industrial applications are in the electrochemical industries where quantities of low-voltage DC power are required. Overall efficiencies should approach 60% and, because of the building-block nature of fuel cells, size is not a factor in efficiency.

Consequently, fuel cells may be well suited to dispersion on a power system, which could have an important bearing on future transmission and distribution system design and costs. It is predicted that, with the effort being expended in fuel cell research and development, cells in sizes up to 100 kilowatts will be available by 1975 at costs of about $200 per kilowatt, and by 1980, costs should reach a level of $100 per kilowatt in sizes up to 1,000 kilowatts (38). Since fuel cells do not require large amounts of cooling water, they present a negligable thermal pollution problem.

5.2.2.6 Fusion Reactor

Thermonuclear fusion consists basically of combining the atoms of the lighter elements at high velocity to form new and heavier elements. Excess energy is released in the process. The velocity of random nuclear particle travel is a function of the temperature, and to secure the needed velocities, temperatures for a controlled thermonuclear reaction range from 40 to 100 million degrees. Since no known materials could contain such temperatures, fusion experiments involve the containment of the hot plasma in a magnetic field. It appears possible that energy so released may be removed directly as electric energy.

The threshold of the fusion reaction, using a mixture of deuterium and tritium, is said to be 40×10^{6}°K for one millisecond (38). The problems therefore, are those of containment and temperature. Although practical fusion power generation applications do not seem to be available in the near future, optimisim currently exists due to recent successes in the U. S. S. R.

The potential of fusion reactors as a commercial

electric power source has not been fully explored; but it appears likely that with the high temperatures involved, an improved efficiency of power generation should result and thermal pollution would be subsequently reduced.

5.2.2.7 Electrogasdynamics

Electrogasdynamics (EGD) is a technique for converting the pressure energy of a flowing gas directly into high-voltage electricity without moving mechanical parts. In its simplest form, the EGD generator consists of a source of ions, usually a corona discharge, and a downstream collector of these ions. The mechanical force of a combustion gas stream drives the ions downstream, where they are picked up on an electrode. Thus, the inside of the pipe through which the combustion gas is flowing becomes part of an electric circuit, where ions are driven downstream from one terminal to the other and through an external circuit. The resistance of the circuit causes an electric field to build up at the downstream terminal. The gas drives the ions downstream against this opposing field. Thus the power in the circuit is the result of mechanical work done by the moving gas. There are many stages in the conversion section through which the gas flows until it is near atmospheric pressures and near normal stack temperatures before discharge to the atmosphere. Based on limited information, an efficiency of 50% and capital cost of $91/kw are predicted for EGD plants (30). Since almost all of the waste heat is rejected to the atmosphere, thermal pollution of water would not be a problem with EGD power generation.

5.3 Uses of Waste Heat

The effects of rejected heat from powerplants are not necessarily

detrimental. A number of constructive and practical uses of this heat source have been suggested and some have been utilized successfully.

Certain fish species have been noted to be attracted to the heated water discharged from powerplants. As a result, angling in the area of some powerplant discharges has been enhanced during most of the year and especially during the winter months.

Aquaculture, which Gaucher (43, p. 293) defines as ". . . a directed effort by man to increase the yield of plants and animals in either fresh or salt water," offers the most logical use of heated cooling water and has been practiced successfully for several years in Russia and Japan. Heated waters from power stations have been used for the commercial production of carp in the U. S. S. R. and have substantially increased the growing season of this species. Prior to the use of power station cooling reservoirs, carp culture was restricted by temperatures to the extreme southern parts of Russia, and even there optimum temperatures prevailed only during six months of the year. Now carp cultivation is practiced successfully in Central Russia in artificially heated waters and at some stations growth is permitted even during the winter months.

Gaucher estimates the yield of fish which might be produced by utilizing the combined cooling water effluent of 790,000 gpm from the Connecticut Yankee and Millstone Point powerplants in Connecticut. Using a figure of 50 pounds of fish produced per year per gpm of cooling water, an annual commercial production potential of 39.5 million pounds of animal flesh is estimated to be possible. Gaucher also indicates that recent advances in the controlled culture of freshwater and marine fish species suggest that the estimate, which is based on the present-day

cold-water trout industry, may be considerably exceeded if fast growing shellfish, crustaceans, or fin fishes are cultivated. Specific species suggested for cultivation include trout, salmon, catfish, pompano, shrimp, oysters, and scallops. A program of oyster cultivation has already begun. On Long Island, over a million young hatchery bred oysters have been placed in a lagoon receiving heated cooling water from the Long Island Lighting Company's fossil fuel powerplant at Northport.

Similar programs are underway in Great Britain. Fast growth of carp, rainbow trout, and brown trout was realized after stocking in the discharged cooling water from the Roosecote Power Station. Yearling trout grew to market size after one summer without supplementary feeding. At another site, sole reared in heated discharge water attained market size in one year, a process which would take three to five years in their natural environment.

In the area of agriculture, studies are underway to determine whether thermal discharges can be used for warm water irrigation - to stimulate plant growth and perhaps to prevent cold weather damage to plants and fruit trees, or to extend the growing season. Smith (92) describes a project currently underway at Oregon State University investigating the use of the earth as a condenser. As envisioned, a closed loop system of pipes, buried underground will carry the rejected heat from the plant and utilize the soil as a heat sink. The system would be sized so that suitable cooling occurs before the water returns to the plant. The effect of the rejected heat on the growth of crops planted in the soil above the cooling water pipes is currently being investigated (using buried electrical cables as a heat source to simulate the cooling water pipes). Results have shown that some of the

plants, including field corn and soy beans, emerge from the soil one to two days sooner in the heated soil. It is estimated that about 20,000 acres of land would be needed in a moderate climate to handle the heated water from a 1000 MWe plant using this cooling method.

Dingman et al. (23) propose using discharged cooling water to de-ice waterways. In particular, they indicate the feasibility of keeping significant reaches of the St. Lawrence Seaway ice-free by the proper placement of nuclear powerplants. Thro (97) elaborates on a similar proposal made by J. G. Biggs of Atomic Energy of Canada Limited. Biggs' plan places large nuclear powerplants (one of 8000 MWe) at the heads of the four canals making up the middle part of the Seaway between Montreal and Buffalo. Deep narrow channels would be built to minimize heat loss. Three additional plants of 2000-, 4000-, and 5000 MWe, would also be built on lakes comprising the western end of the Seaway. The waste heat from these plants would allow the Seaway to operate an additional six weeks beyond the present season - all months except February and March, when the Great Lakes are frozen.

Using discharged cooling water to heat the influent to public water works is another possible use of waste heat and a money-saving one. Hoak (50) indicates that the amount, and thus cost, of chemicals necessary to treat a municipal water supply can be reduced to the extent that there is a saving of 30¢ to 50¢ in treatment costs per million gallons, for each 10°F rise in temperature. Fair and Geyer (35) give typical treatment costs as $15 per million gallons. Therefore heating the influent by 20°F could mean a savings of about 6.5% in treatment costs.

The use of waste heat in the form of exhaust steam offers another practical and economical solution to the heat rejection problem. A

powerplant turbine may be designed as a non-condensing, or back-pressure, turbine and exhaust its steam at a much higher temperature and pressure than a conventional condensing unit. This exhaust steam is useful for a variety of processes and saves the burning of extra fuel for the generation of steam alone. Desalination, home heating, and industrial processes are practical uses for the exhaust "process" steam and almost all of the waste heat is thus utilized or rejected to the atmosphere directly and not to cooling water. Warren (109) cites a recent application of this process by the Public Service Electric and Gas Company of New Jersey in their Linden Plant. Two units are installed which furnish electric power for the Public Service system and simultaneously furnish millions of pounds of steam per hour for an adjacent oil refinery. More than 20 years ago, the Pacific Gas and Electric Co. found they could greatly reduce their consumption of fuel per kwhr chargeable to power by selling their exhaust steam to oil refineries instead of letting it go to waste and heat up San Francisco Bay.

A recent study by the Oak Ridge National Laboratory (81) investigated using exhaust process steam for urban space heating.

Jones (85) discusses the economics involved in this trade-off of electrical generating capacity for steam power in his study of a reverse situation - whether an industry requiring steam should generate its own electricity.

Other areas suggested for the use of waste heat include refrigeration, air-conditioning, sewage treatment, de-icing sidewalks and roadways, and heating swimming pools.

The variety of possible benefits realizable from the proper use of discharged waste heat suggests that "thermal pollution" is not the most

fitting name for this subject because of the connotation attached to pollution. "Thermal enrichment" has been suggested. "Thermal effects" might be more equitable.

5.4 Water Temperature Restrictions

The Federal Water Pollution Control Act, passed in 1948 and subsequently amended (last in 1966), gives the Department of the Interior the authority to control thermal pollution. Provisions added by the Water Quality Control Act of 1965 required each state to establish water quality standards and a plan for implementing these standards subject to approval by the Secretary of the Interior.

Water quality standards protect legitimate uses of the water through application of numerical and narrative limits on pollutants, including heat, and the specification of necessary treatment and control measures. To prevent damage to aquatic life and other uses in interstate waters from thermal pollution, all of the 50 states, the District of Columbia, Guam, Puerto Rico, and the Virgin Islands submitted to the Department of Interior for approval water quality standards, including temperature criteria. Powell and Waugaman (83) report that as of January 1969, the water quality standards of 48 states were approved in whole or in part.

Each state criterion is unique, but their temperature requirements show certain similarities. There is generally a maximum temperature limit (93°F is a typical limit), a maximum allowable increase over ambient temperature (a common figure is 5°F), and a maximum rate of temperature change (a typical value is 2°F/hr). As an example of specific criteria, New York State proposed the following set of standards to the Department of the Interior for Federal approval (110):

1. Thermal discharges into waters classified for trout are

prohibited.

2. Maximum allowable water temperature is 90°F, in both fresh and salt waters.

3. In fresh water, a thermal discharge cannot raise stream temperature at the boundary of the mixing zone higher than 86°F nor exceed a maximum increase of 5°F. In salt water, the maximum temperature limit at the edge of the mixing zone is 83°F and the maximum increase is 4°F, with the qualification that in the summer months when the natural water temperature approaches 85°F, the maximum allowable increase is 1.5°F.

4. The mixing zone must be restricted such that a minimum 50% of stream cross-section and/or volume of flow in the stream is unaffected by the thermal discharge. A minimum one-third of the mixing zone surface area must be maintained below the allowable maximum 5°F temperature rise or maximum 86°F stream temperature after mixing, whichever is less.

5. Maximum rate of change of water temperature of 2°F per hour, not to exceed 9°F in any 24 hour period for both fresh and salt waters.

This last restriction concerning rate of change of temperature has been subsequently withdrawn by New York State after objections from the electric power companies. The power companies' argument was stated as follows (110, p. 20):

> With respect to utility operations, operating requirements of power plants which require full use of the stream. . . cannot tolerate the limited rate of change of 2°F/hr specified. In order to maintain a stable and reliable electric power grid, wide variations in loading are necessary. These variations occur on a daily, weekly, and seasonal basis. Thermal units are generally brought to power over a period of approximately four hours. However, on

> occasion, these units must respond more rapidly. The temperature rise through the condenser as a result of these load swings is reflected outside the mixing zone at a rate and amount dependent on the ratio of water quantity diverted to that available in the water body.
>
> The restriction is not biologically necessary. Evidence in the literature. . . indicates that the rate of rise is not of biological concern unless the temperature is close to the lethal temperature for a particular species. Such high temperatures would exist only in a limited number of streams during a very limited period of the year. Where the problem is then one of very localized and limited application. . . it (should) be dealt with by appropriate stream classification, and not be an across-the-board penalty on. . . utility operations applicable to all streams.

The states have not generally specified the implementation measures necessary to insure compliance with the temperature criteria. The standards require that dischargers of heated wastes take the necessary action to meet the water quality criteria and specific implementation guidance was omitted on the basis that the effect of waste heat discharge on particular waterways must be studied on a case-by-case basis.

One potentially effective control tool is the Federal or State lease, license, permit, or contract. The review process attendant to the issuance of a lease, license, permit, or contract affords an opportunity to examine, at an early stage in the development of a proposed project, its impact on the environment and to prevent or minimize damage from occuring. At this stage, the water quality impact of the project can be studied by the water pollution control officials of the affected state and the Department of the Interior, and industry can receive expert advice to insure compliance with water quality standards. The licensing agency can require the installation of the thermal pollution control measures which are immediately necessary to protect water quality and water uses prior to construction and operation. Also, it is a means of continuing control by the licensing agency. The licensee is

required by the licensing agency to comply with the conditions of his license. These conditions would, under this method of control, include provisions designed to insure uniform compliance on a continuing basis with the legislated water temperature restrictions. The Energy Policy Staff (32) notes that the water pollution control laws of 35 states already require that a discharge permit be obtained to construct and/or operate, and discharge municipal and industrial wastes. However, it is not known how many of these permits are being applied to cooling water discharges.

The Federal Power Commission (FPC) under the Federal Power Act requires that public use and environmental factors be considered in the issuance of its licenses for hydroelectric powerplants (101). Fossil fuel plants which are the current major contributor to thermal pollution, however, are not licensed by the FPC except where they are part of a federally licensed hydro project. The Department of the Army, Corps of Engineers, under provisions of the Rivers and Harbors Act, grants permits for dredging, filling, and excavation in the navigable waters of the United States (88). Where a cooling water intake or discharge structure extends to such waters, a Corps of Engineers permit is required. The Secretary of the Army and the Secretary of the Interior have entered into a memorandum of understanding under which the views of Bureaus of the Department of the Interior will be obtained relative to control and prevention of water pollution. The Corps of Engineers has included provisions relative to meeting the applicable water quality standards in permits issued for construction at electric powerplants.

In September 1968, the Federal Power Commission issued a significant order with respect to the application of the Arkansas Power and

Light Co., for FPC approval to use lands and waters of a federally licensed project at Lake Catherine. The application by Arkansas Power and Light Co., was concerned with a cooling water facility to be built in connection with a proposed addition to one of the company's steam-electric powerplants (101). The order approving the application requires the power company to finance a study, in cooperation with appropriate Arkansas State agencies, and the Federal Water Pollution Control Administration and the Bureau of Sport Fisheries and Wildlife of the Department of the Interior, to determine the effect of heat load mixing in Lake Catherine. The study is to investigate the effect of the heat load on fish and wildlife resources before and after the installation and operation of the cooling water system. The power company is required to report the results of the study and proposals for protection of the waters of the lake, downstream waters, and fish and wildlife resources by July 1971, and to advise the FPC immediately during the course of the study of any adverse effects of the plant, with proposals for remedial action. The FPC reserved the right to order appropriate remedial actions if the power company fails to act. This order is an example of how the licensing authority can be utilized to protect the environment.

The Atomic Energy Commission (AEC) which licenses nuclear powerplants, lacks a statutory base for considering and conditioning a license in the case of thermal pollution although it does consider radiological effects. The AEC does, however, provide applicants with comments made available by the agencies of the Department of the Interior which review construction permits and operating licenses with respect to their areas of interest and responsibilities. Under this agreement, the U. S. Fish and Wildlife Service has provided comments to the AEC regarding the

potential effects of heated discharges on fish and other aquatic life, and wildlife.

Comments on the effects of heated discharges are transmitted by the AEC to the power companies with the request that they discuss them with state and Federal Control agencies on a voluntary basis. The AEC does not believe, however, that it can require modifications in the license application for this purpose and views the problems of thermal pollution, esthetics, and effects on other uses in the area as irrelevant to the issues in the case, or outside their jurisdiction, and as precluding intervention by the Department of the Interior or anyone else on these grounds (101). If the applicant fails to heed the Federal and state advice concerning thermal pollution on a voluntary basis and insists on a license, it appears that the AEC has no alternative but to grant it. However, a recent agreement by the Department of the Interior, AEC, and the Joint Congressional Committee on Atomic Energy to promote legislation supporting state certification of thermal discharges promises to eliminate lack of licensing control over thermal pollution, particularly the current lack of control with respect to nuclear plants (93). According to the proposed legislation, an applicant for a federal permit or license to conduct any activity that may result in heated and other discharges into the waters of the United States shall provide the licensing agency with certification from the appropriate state or interstate water pollution control agency that such activity will be conducted in a manner that shall insure compliance with applicable water quality standards.

The controversy over thermal pollution focuses on the temperature standards that have been adopted or proposed by the states. Electric

utilities do not fully agree with them on the grounds that there is not enough data on the effects of heated effluents on aquatic life. They would prefer to set interim guidelines rather than permanent standards. The Department of the Interior maintains that the information now available is adequate for setting standards. As their argument for provisional rather than permanent standards, the utilities maintain that temperature-tolerance levels and lethal temperatures are known only for a limited number of fish and that this data is too scattered and indefinite to be of practical value (85).

A major item of contention is the mixing zone criteria. The power industry believes that temperature criteria should be applied to water at the end of the mixing zone i.e., the area where the heated effluent mixes horizontally and vertically with the receiving water. Some states (New York, Maine, Pennsylvania and others) recognize a mixing zone and apply their temperature criteria at the end of the zone. However other states, such as New Hampshire, require compliance with their temperature restrictions as soon as the heated water reaches the water source.

The Department of the Interior's position on mixing zones is as follows (101, p. 989):

> Any barrier to migration and the free movement of the aquatic biota can be harmful in a number of ways. Such barriers block the spawning migration of anadromous and catadromus species. Many resident species make local migrations for spawning and other purposes and any barrier can be detrimental to their continued existence. The natural tidal movement in estuaries and downstream movement of planktonic organisms and of aquatic invertebrates in flowing fresh waters are important factors in the repopulation of areas and the general economy of the water. Any chemical or thermal barrier destroys this valuable source of food and creates unfavorable conditions below or above it.
>
> It is essential that adequate passageways be provided at all times for the movement or drift of the biota. Water quality criteria favorable to the aquatic community must be maintained at all times

in these passageways. It is recognized, however, that certain areas of mixing are unavoidable. These create harmfully polluted areas and for this reason it is essential that they be limited in width and length and be provided only for mixing. The passage zone must provide favorable conditions and must be in a continuous stretch bordered by the same bank for a considerable distance to allow safe and adequate passage up and down the stream, reservoir, lake, or estuary for free-floating and drift organisms.

The width of the zone and the volume of flow in it will depend on the character and size of the stream or estuary. Area, depth, and volume of flow must be sufficient to provide a usable and desirable passageway for fish and other aquatic organisms. Further, the cross-sectional area and volume of flow in the passageway will largely determine the percentage of survival of drift organisms. Therefore, the passageway should contain preferably 75 percent of the cross-sectional area and/or volume of flow of the stream or estuary. It is evident that where there are several mixing areas close together they should all be on the same side so the passageway is continuous. Concentrations of waste materials in passageways should meet the requirements for the water.

The shape and size of mixing areas will vary with the location, size, character, and use of the receiving water and should be established by proper administrative authority. From the standpoint of the welfare of the aquatic life resource, however, such areas should be as small as possible and be provided for mixing only. Mixing should be accomplished as quickly as possible through the use of devices which ensure that the waste is mixed with the allocated dilution water in the smallest possible area. At the border of this area, the water quality must meet the water quality requirements for that area. If, upon complete mixing with the available dilution water these requirements are not met, the waste must be pretreated so they will be met.

As far as the electric power industry is concerned, legislated environmental constraints, such as water temperature standards, are more evolutionary than surprising. The industry has voluntarily demonstrated its concern for the preservation of a healthy and pleasant environment from before the time the Water Quality Control Act of 1965 was enacted. This concern was, and is, exemplified by a continuing study (84) financed by the Indianapolis Power and Light Company (IPALCO). In 1964 IPALCO decided to undertake a study of the biological effects of the discharge of waste heat to the White River in Indiana from a new powerplant; the first unit of which was to be placed in operation in 1967.

The Indiana University Water Resources Research Center was contracted to conduct the study extending from June, 1965, through May, 1971, a total of six years. The completed study will have spanned two years before any heat was added to the river, two years with just one generating unit in operation, and two years with two units in operation. Studies such as this one are not inexpensive. McKee (66) of the Potomac Electric Power Co. has stated that his company has spent in excess of $3,500,000 on consultants, research, and studies to determine how to protect both the Potomac and Patuxent Rivers in the vicinity of two of its plants.

Water quality standards provide an objective basis for determining what measures are necessary for the control of thermal pollution. Their establishment at the state level with review and approval at the Federal level should balance society's many and varied interests in water while assuring a degree of consistency in its quality. To permit both economic development and the protection of the aquatic environment, water quality standards have to be both technically achievable and economically reasonable. The water quality criteria established for the designated water uses and the plans for implementation will be enforceable by the states and the Federal Government under enforcement provisions of their enabling acts.

VI. SUMMARY

Public concern over the problems of air and water pollution has become an important factor in the location, design, and operation of steam-electric powerplants. Although thermal pollution of water has historically been of little significance, the rapidly increasing electric power demand and the large quantities and concentrations of rejected heat that will be associated with the large powerplants of the future have focused an increasing amount of attention on this aspect of environmental pollution.

Thermal pollution results from both fossil fuel and nuclear powerplants; however current water-cooled nuclear powerplants reject about 50% more heat per kwhr produced because of lower plant thermal efficiencies. In addition, the proportion of total electric power produced by the increasing numbers of nuclear powerplants is expected to exceed that produced by fossil fuel powerplants by the year 2000. However, the development of liquid metal cooled, gas cooled, and molten salt cooled reactors has progressed to the stage where it is expected that nuclear powerplants using these types of reactors and having thermal efficiencies equal to those of fossil fuel powerplants will be commercially feasible in the 1980's. The heat rejection per kwhr of electrical power produced will then be the same for nuclear powerplants as for fossil fuel powerplants.

The effects of the discharge of heated cooling water from steam-electric powerplants can be harmful or beneficial. In general, the adverse effects of thermal pollution on aquatic life stem directly from the rise in temperature of the water, and the decrease in the capacity of the water to hold dissolved oxygen resulting from the temperature

rise. Knowledge of the exact effects of elevated water temperatures on aquatic life is incomplete but sufficient to predict that even a moderate increase in water temperature may be disastrous to certain aquatic species.

The large and growing amounts of waste heat produced can be used to beneficial ends by the use of proper waste heat management techniques. Fish farming, using waste heat from powerplants to stimulate growth, is a technique that has already been utilized successfully.

The ability to dispose of waste heat in an acceptable manner depends on the type of powerplant cooling system used. Onshore cooling systems, such as cooling towers, eliminate thermal pollution but are generally more costly than using natural water sources on a once-through basis. However, the use of an onshore cooling system often permits optimum powerplant siting with respect to fuel and transmission costs which may more than offset the increased costs of the onshore cooling system.

To control the effects of injecting large amounts of heat into the water environment, the states, in cooperation with the U. S. Department of the Interior's Water Pollution Control Administration, have adopted temperature limitations for the Nation's waterways. These limitations provide an objective basis for determining what cooling measures are necessary to control thermal pollution.

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APPENDIX A

Heat Balance Calculations, B & W Nuclear Powerplant

All numerical values in this Appendix, except those calculated, are taken from a plant heat balance diagram obtained from the Babcock and Wilcox Company, Power Generation Division, Lynchburg, Virginia.

1. Heat Added:

Total mass flow rate through steam generator, W_s = 11, 368,367 lbm/hr

Steam generator inlet feedwater temperature and pressure: 455.1°F, 885 psia

Steam generator inlet feedwater enthalpy = 436.1 Btu/lbm = h_{feed}

Steam exit temperature and pressure: 565°F, 885 psia

Steam exit enthalpy = 1231.5 Btu/lbm = h_{steam}

Heat added = $Q_A = W_s\ (h_{steam} - h_{feed})$

$$Q_A = 11.368\ 367\ 10^6\ \frac{\text{lbm}}{\text{hr}}\ (1231.5 - 436.1)\ \frac{\text{Btu}}{\text{lbm}}$$

$$Q_A = 9050\ \ 10^6\ \frac{\text{Btu}}{\text{hr}}\ \text{HEAT ADDED}$$

2. Heat Rejected:

Condenser Heat Balance

Influent Source	Mass Flow Rate ($\dot{m}_i$), lbm/hr	Inlet enthalpy (h_i), Btu/lbm
Main Turbine Exhaust	6,110,378	993.7
Feedwater heater drains	1,989,464	75.5
Feed pump turbine exhaust	128,184	1000.8
Turbine gland seal regulators leakoff	7,200	1155.9
Steam jet air ejector drains	6,300	180.2

Effluent	Mass Flow Rate lbm/hr	Outlet enthalply (h_o), Btu/lbm
Condensate	8. 241,526	59.72

Condenser pressure: 1.5" hg absolute
Condenser temperature: 91.7°F

$$\text{Total Heat Rejected} = \sum_i Q_{Ri} = \sum_i \dot{m}_i (h_i - h_o) = Q_R$$

$\dot{m}_i$ (lbm/hr)	·	$(h_i - h_o)$ Btu/lbm	=	Q_{Ri} Btu/hr
6,110,378	·	(993.7 - 59.72)	=	314.2 10^6
1,989,464	·	(75.5 - 59.72)	=	5710.0 10^6
128,184	·	(1000.8 - 59.72)	=	.76 10^6
7.200	·	(1155.9 - 59.72)	=	121.0 10^6
6,300	·	(180.2 - 59.72)	=	7.89 10^6

$$\text{Total Heat Rejected} = Q_R = 6.154\ 10^9 \text{ Btu/hr}$$

3. Nuclear Plant Thermal Efficiency (e):

$$e = \frac{Q(\text{added}) - Q(\text{rejected})}{Q(\text{added})} = \frac{9050\ 10^6 \text{ Btu/hr} - 6154\ 10^6 \text{ Btu/hr}}{9050\ 10^6 \text{ Btu/hr}}$$

$$e = .32 = 32\% = \text{Plant thermal efficiency}$$

APPENDIX B

Heat Balance Calculations, TVA Fossil Fuel Powerplant

All numerical values in this Appendix, except those calculated, are taken from a plant heat balance diagram in reference 79.

1. Heat Added:

Total feedwater mass flow rate into boiler = $\dot{W}_f$ = 6,335,200 lbm/hr

Reheat steam flow = $\dot{W}_h$ = 4,475,500 lbm/hr

Boiler inlet feedwater temperature and pressure = 550.1°F, 3515 psia

Boiler inlet feedwater enthalpy = 550 Btu/lbm = h_{feed}

Outlet steam temperature and pressure = 1000°F, 3515 psia

Outlet steam enthalpy = 1420 Btu/lbm

Inlet reheat steam temperature and pressure = 551.7°F, 600 psia

Inlet reheat steam enthalpy = 1256 Btu/lbm

Outlet reheat steam temperature and pressure = 1000°F, 540 psia

Outlet reheat steam enthalpy = 1518 Btu/lbm

$$Q_A = \text{total heat added} = \sum_i Q_{Ai} = \sum_i \dot{W}_i \,(h_{out} - h_{in})_i$$

$$Q_A = \dot{W}_f \left(h_{out}(\text{steam}) - h_{in}(\text{feed})\right)$$

$$+ \dot{W}_h \left(h_{out}(\text{reheat steam}) - h_{in}(\text{reheat steam})\right)$$

$$Q_A = 6{,}335{,}200 \; \frac{\text{lbm}}{\text{hr}} \; (1420 - 550) \; \frac{\text{Btu}}{\text{lbm}}$$

$$+ \; 4{,}475{,}500 \; \frac{\text{lbm}}{\text{hr}} \; (1518 - 1256) \; \frac{\text{Btu}}{\text{lbm}}$$

$$\text{Total Heat Added, } Q_A = 6660 \; 10^6 \text{ Btu/hr}$$

2. <u>Heat Rejected</u>:

Condenser Heat Balance

Influent Source	Mass Flow Rate ($\dot{m}_i$), lbm/hr	Inlet enthalpy (h_i), Btu/lbm
Main turbine exhaust	3,789,600	1101.5
Feedwater heater drains	574,600	71.0
Turbine gland leak-off	4,400	99.7

Effluent	Mass Flow Rate lbm/hr	Outlet enthalpy h_o, Btu/lbm
Condensate	4,368,600	59.72

Condenser pressure: 1.5" Hg abs.

Condenser temperature: 91.7°F

$$\text{Total Heat Rejected, } Q_R = \sum_i Q_{Ri} = \sum_i \dot{m}_i (h_i - h_o)$$

$\dot{m}_i$ (lbm/hr)	·	$(h_i - h_o)$Btu/lbm = Q_R Btu/hr
3,789,000	·	(1161.5 - 59.72) = 3946.00 10^6
574,600	·	(71.0 - 59.72) = 4.94 10^6
4,400	·	(99.7 - 59.72) = .18 10^6

Total Heat Rejected = Q_R = 3.950 10^9 Btu/hr

3. <u>Fossil Fuel Plant Efficiency</u> (e):

$$e = \frac{Q_A - Q_R}{Q_A} = \frac{6660\ 10^6 - 3950\ 10^6}{6660\ 10^6}$$

Plant Thermal Efficiency, e = .41 = 41%

APPENDIX C

Cooling Water Requirements, B & W Nuclear Powerplant

Heat rejection rate, $Q_R = 6.154 \cdot 10^9$ Btu/hr

Specific heat of cooling water, $C_p = 1$ Btu/lbm°F

Assume a 20°F rise in cooling water temperature through the condenser:

$\Delta T = 20°F$

Cooling water flow rate = $\dot{W}$ (lbm/hr or gal/min or ft^3/sec)

Now: $$Q_R = \dot{W} C_p \Delta T$$

Or: $$\dot{W} = \frac{Q_R}{C_p \Delta T}$$

Therefore: $$\dot{W} = \frac{6.154 \cdot 10^9}{1 \cdot 20} \; \frac{\text{Btu}}{\text{hr}} \; \frac{\text{lbm°F}}{\text{Btu}} \; \frac{}{\text{°F}} \; \frac{\text{hr}}{60 \text{ min}}$$

$$\dot{W} = 5.125\ 10^6 \; \frac{\text{lbm}}{\text{min}} \cdot \frac{\text{gal}}{8.33 \quad \text{lbm}}$$

$$\dot{W} = 615{,}000 \text{ gal/min}$$

Or: $$\dot{W} = 615{,}000 \; \frac{\text{gal}}{\text{min}} \cdot \frac{\text{min}}{60 \text{ sec}} \; \frac{\text{ft}^3}{7.48 \quad \text{gal}}$$

$$\dot{W} = 1370 \; \frac{\text{ft}^3}{\text{sec}}$$